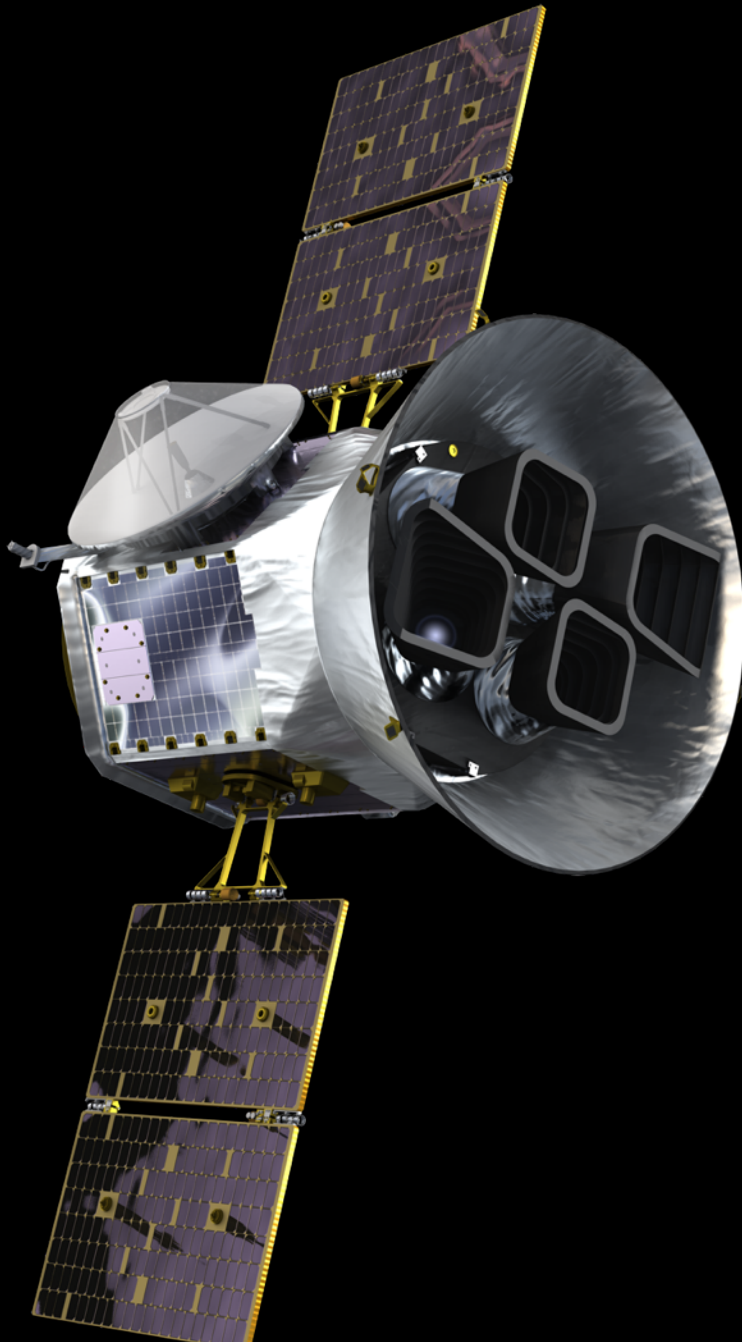


TESS

Deep Depletion CCD Detector Requirements for the Transiting Exoplanet Survey Satellite

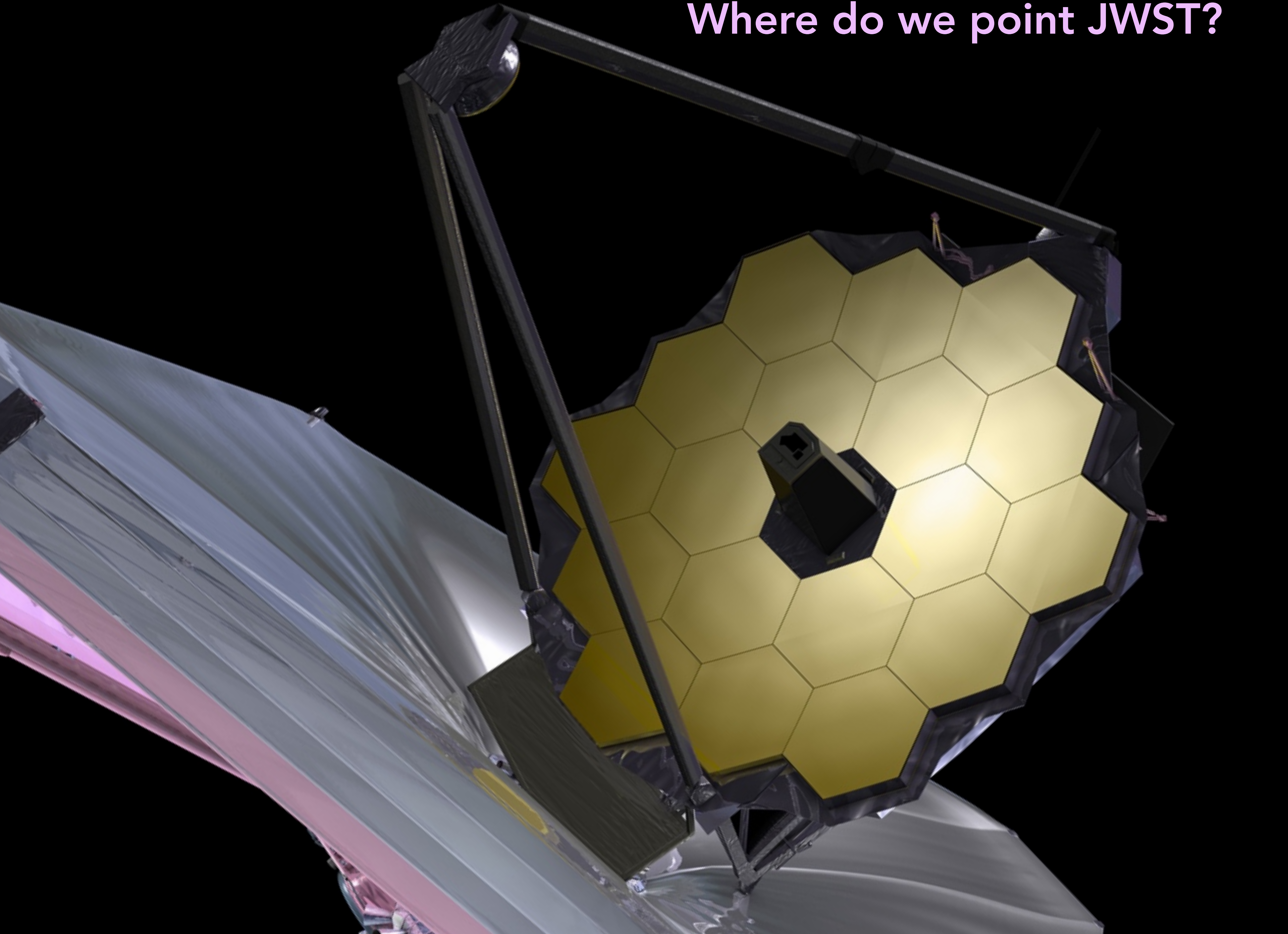
George Ricker (PI, MIT)
on behalf of the TESS Science & Instrument Teams

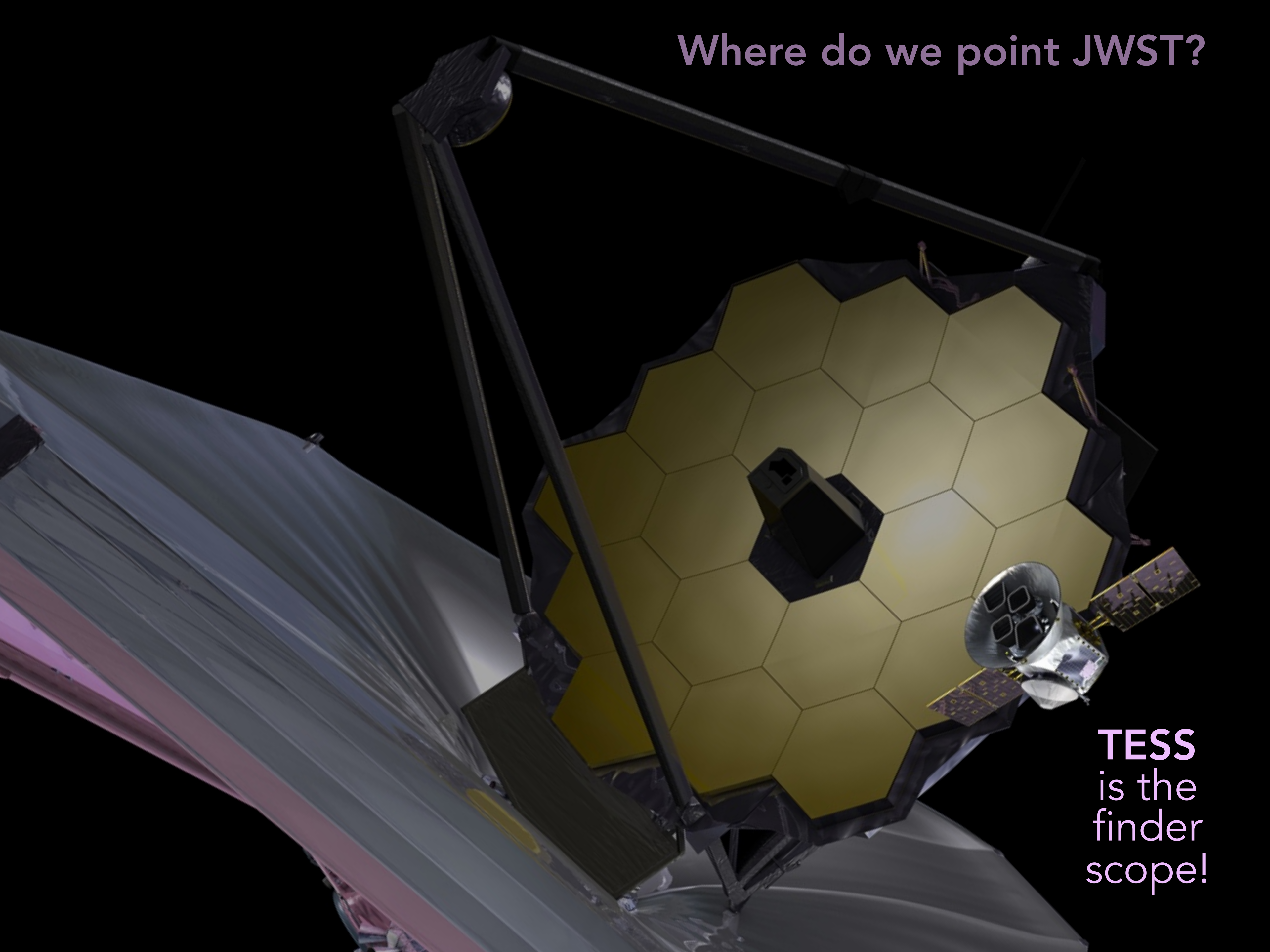
PACCD2016 Conference — BNL
2 December 2016

collaboration including:
MIT/MKI, MIT/LL, NASA Goddard, NASA Ames, Orbital ATK, STScI, SAO, MPIA-Germany, Las Cumbres Observatory, Geneva Observatory, OHP-France, University of California, University of Florida, Aarhus University-Denmark, Harvard College Observatory, Princeton University, Vanderbilt University...

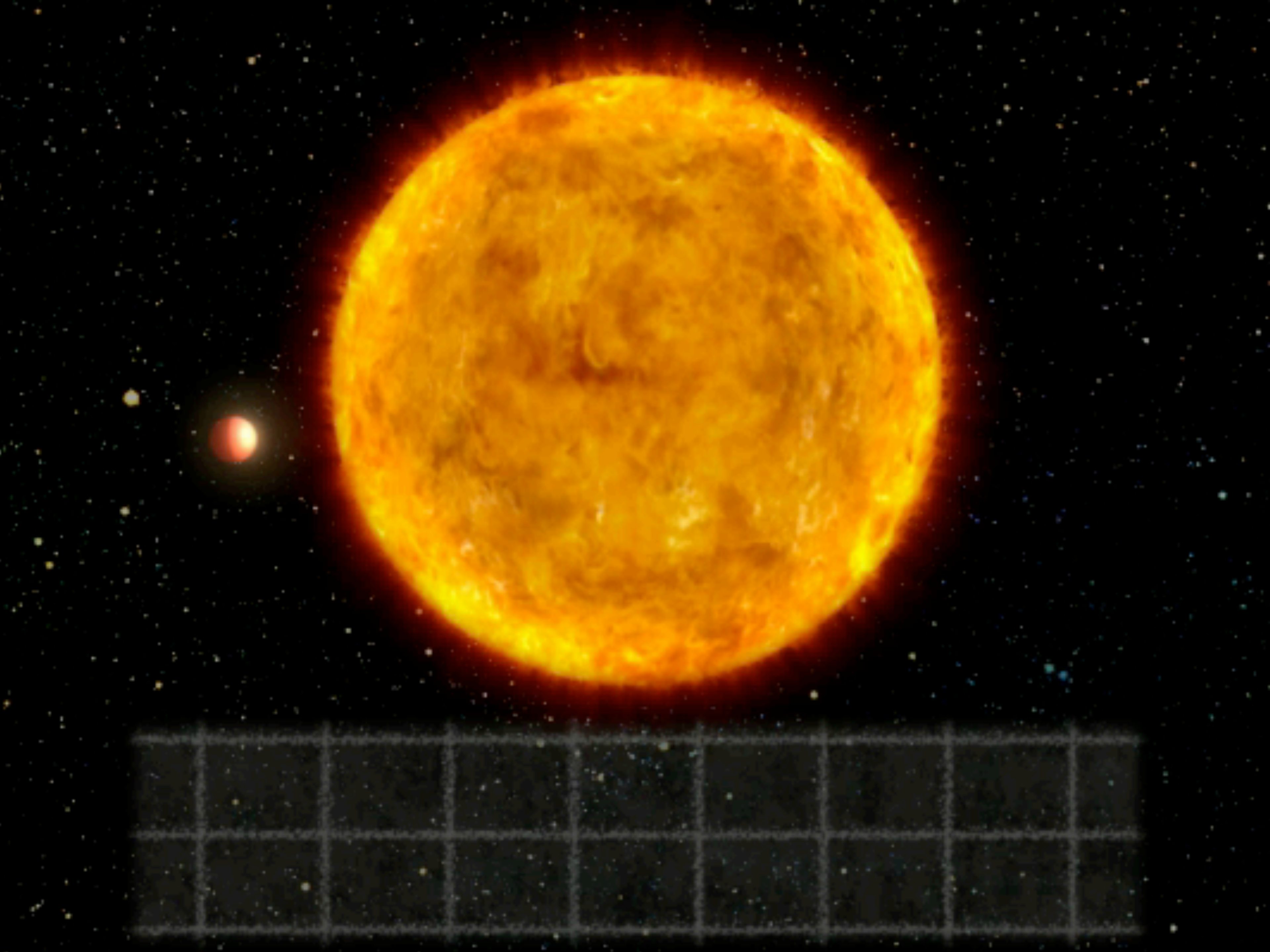
TESS: A Bridge to the Future...

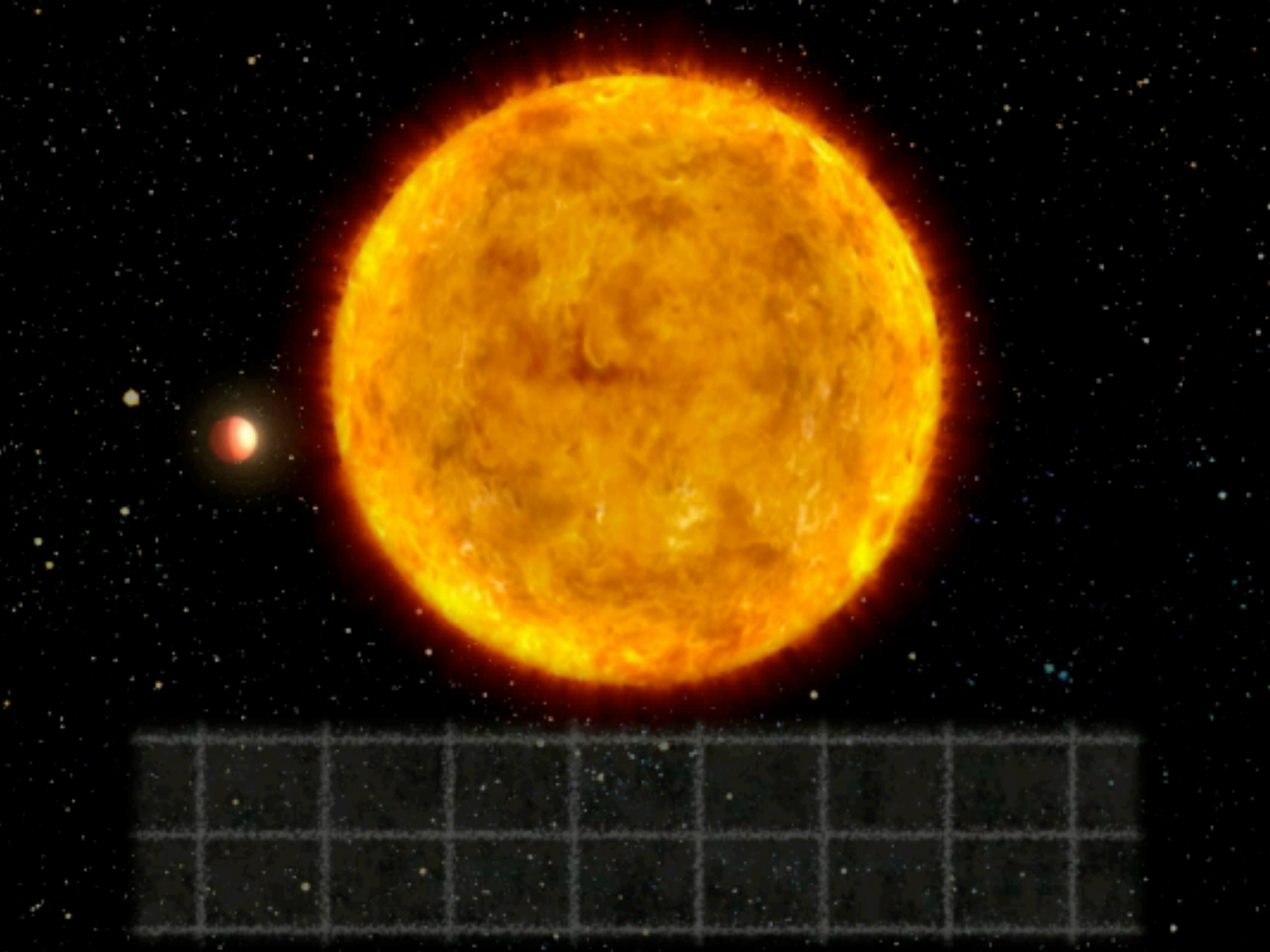
Where do we point JWST?

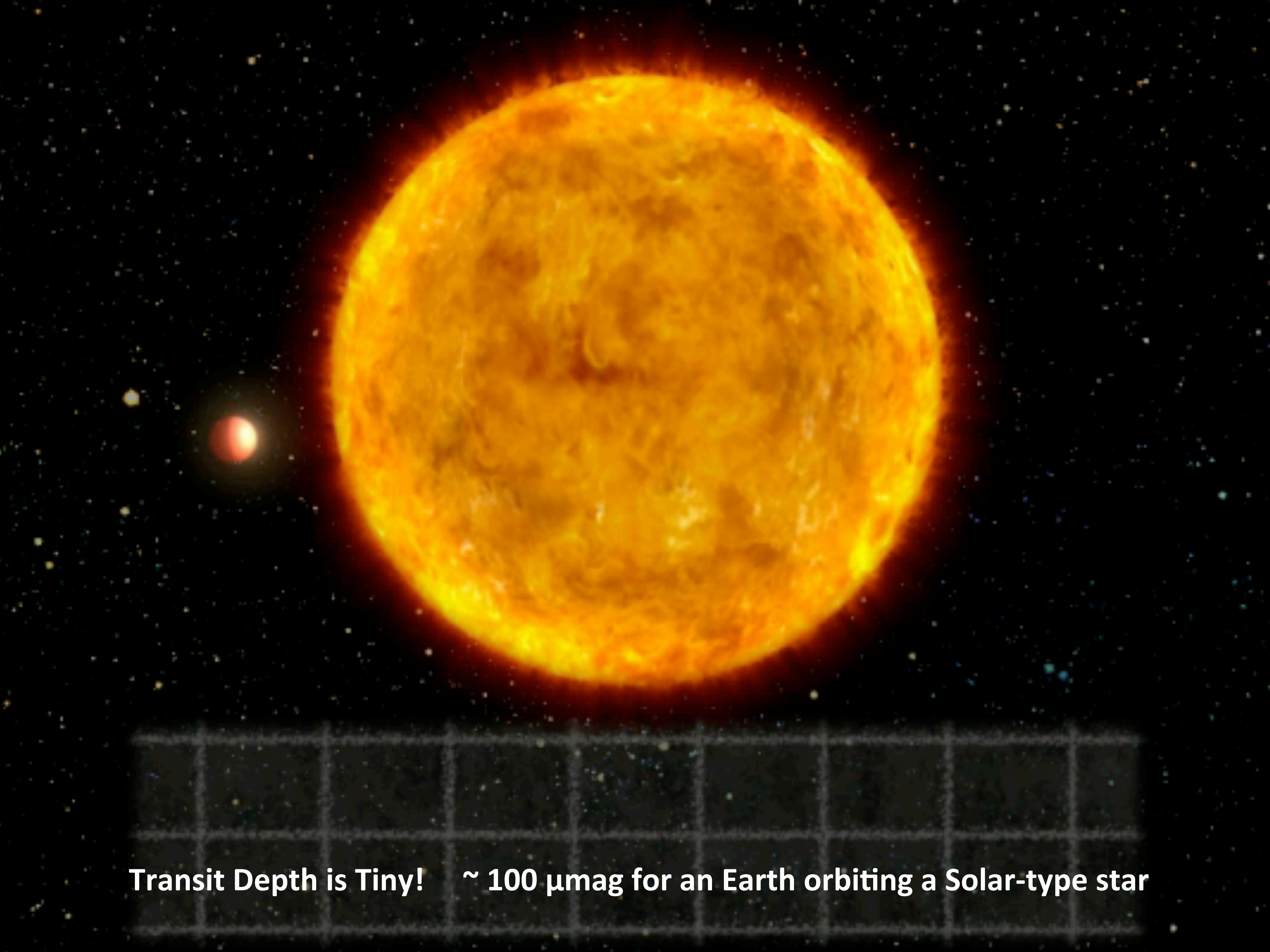



Where do we point JWST?
TESS
is the
finder
scope!

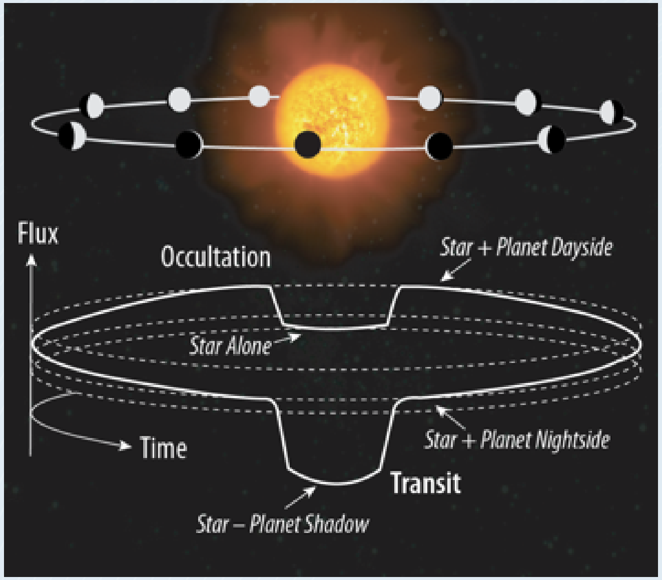
What is a Transit?






Transit Depth is Tiny!   ~ 100 μmag for an Earth orbiting a Solar-type star

So Many Stars...But Some Are Special!



Primary Goal: Discover Transiting Earths and Super-Earths Orbiting Bright, Nearby Stars

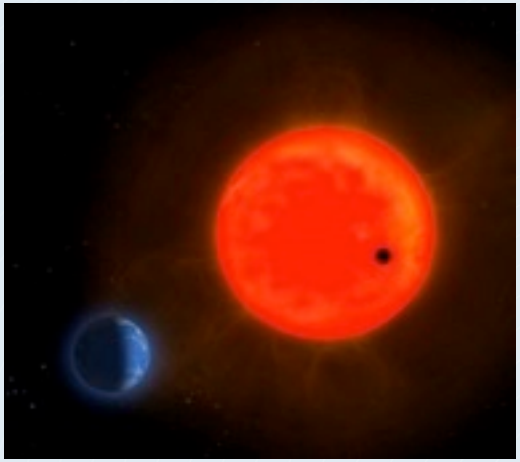
- *Rocky Planets & Water Worlds*
- *Habitable Planets*

Discover the "Best" ~1000 **Small** Exoplanets

- *"Best" Means "Readily Characterizable"*
  - *Bright Host Stars*
  - *Measurable Mass & Atmospheric Properties*
- *Less than a dozen small transiting exoplanets orbiting bright hosts are presently known*

Large Area Survey of Bright Stars

- *Sun-like stars: $I_c \lessapprox 2$ to $I_c = 12$ magnitude*
- *M dwarfs known within ~200 light-yrs ($I_c \lessapprox 14$)*
- *"All sky" observations in 2 years:*
  - *> 200,000 target stars at <2 min cadence*
  - *> 20,000,000 stars in full frames at 30 min cadence*



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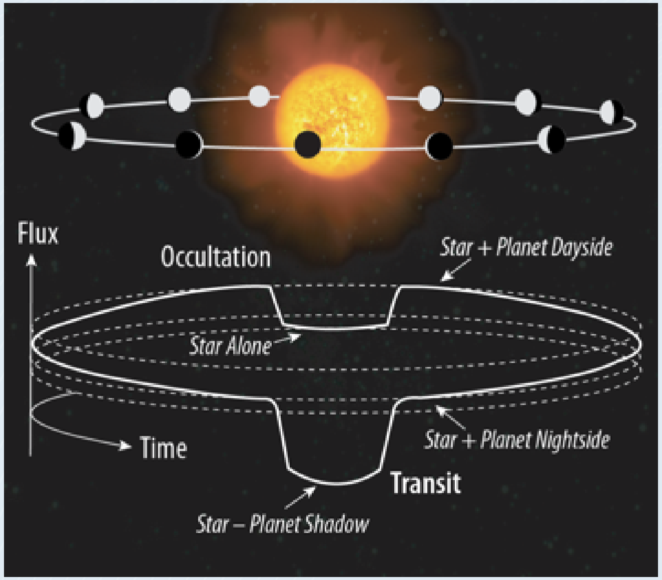

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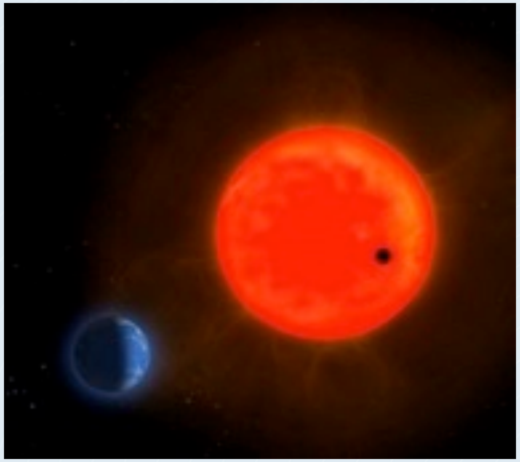

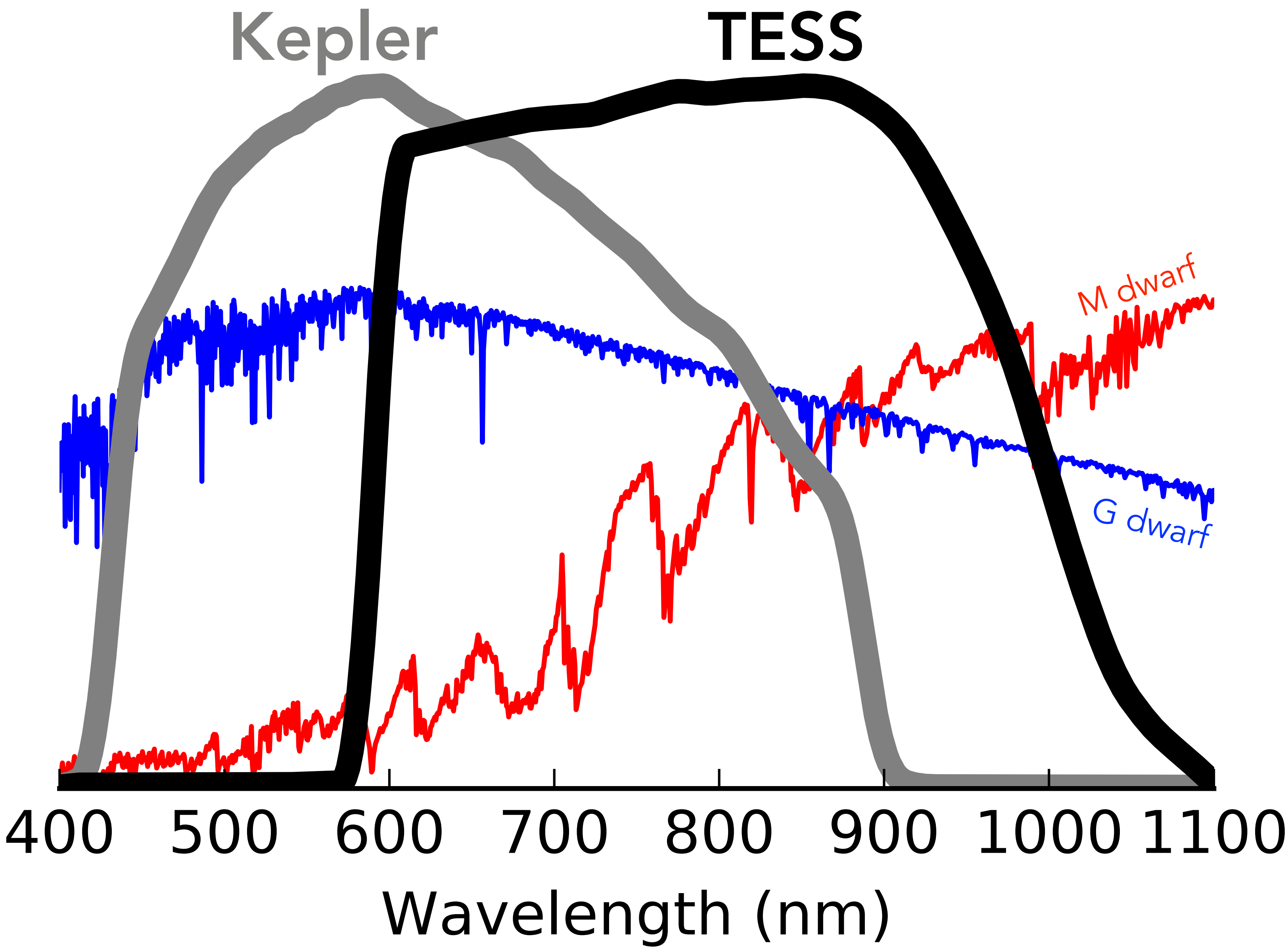

Ricker et al. (2014), Sullivan et al. (2015)

TESS Stars Will Be Brighter than Kepler Stars

2009

2017

TESS Stars Will Be Brighter than Kepler Stars

- How do we arrange for brighter stars?
  - *By design in two ways...*

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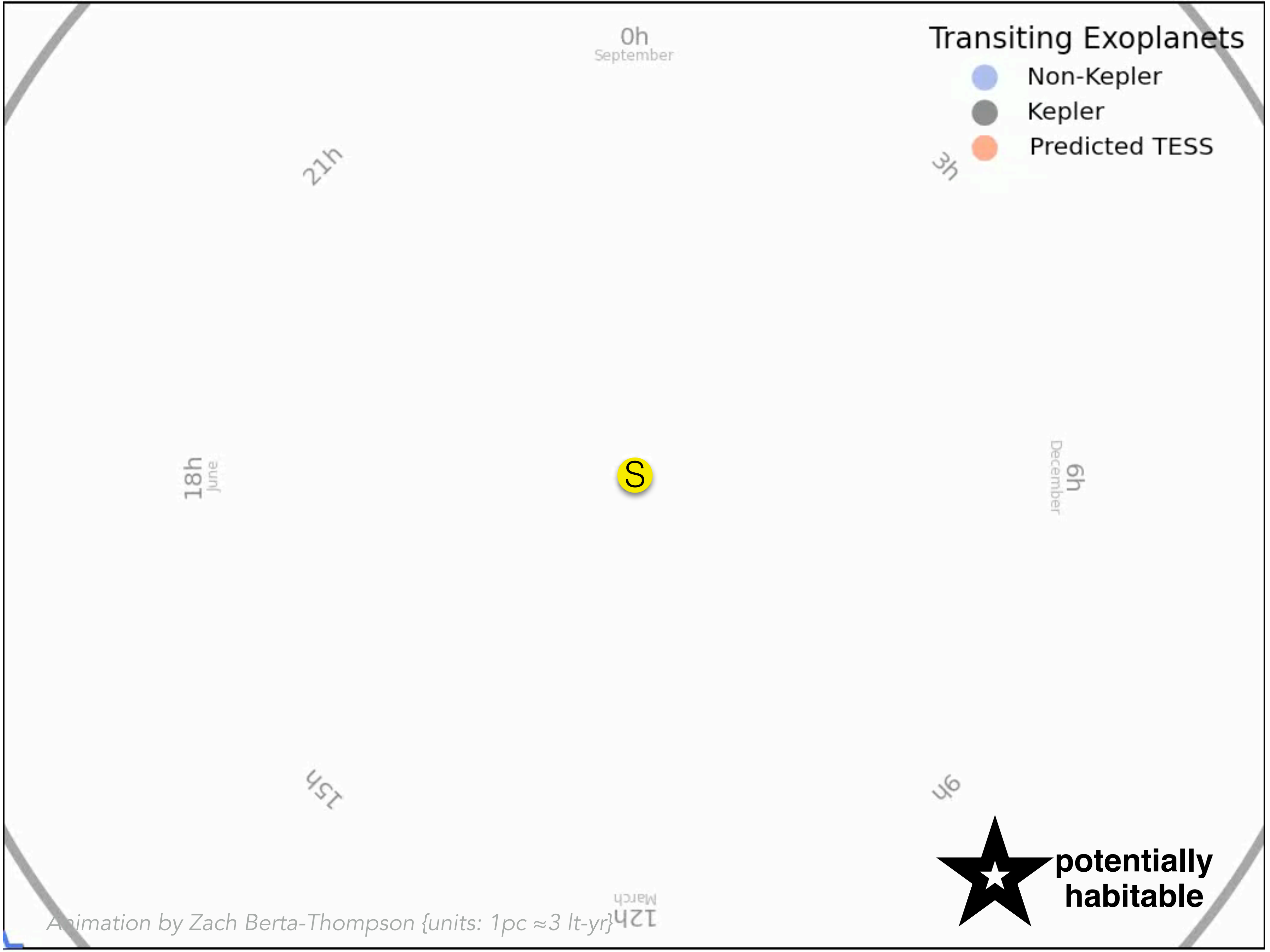
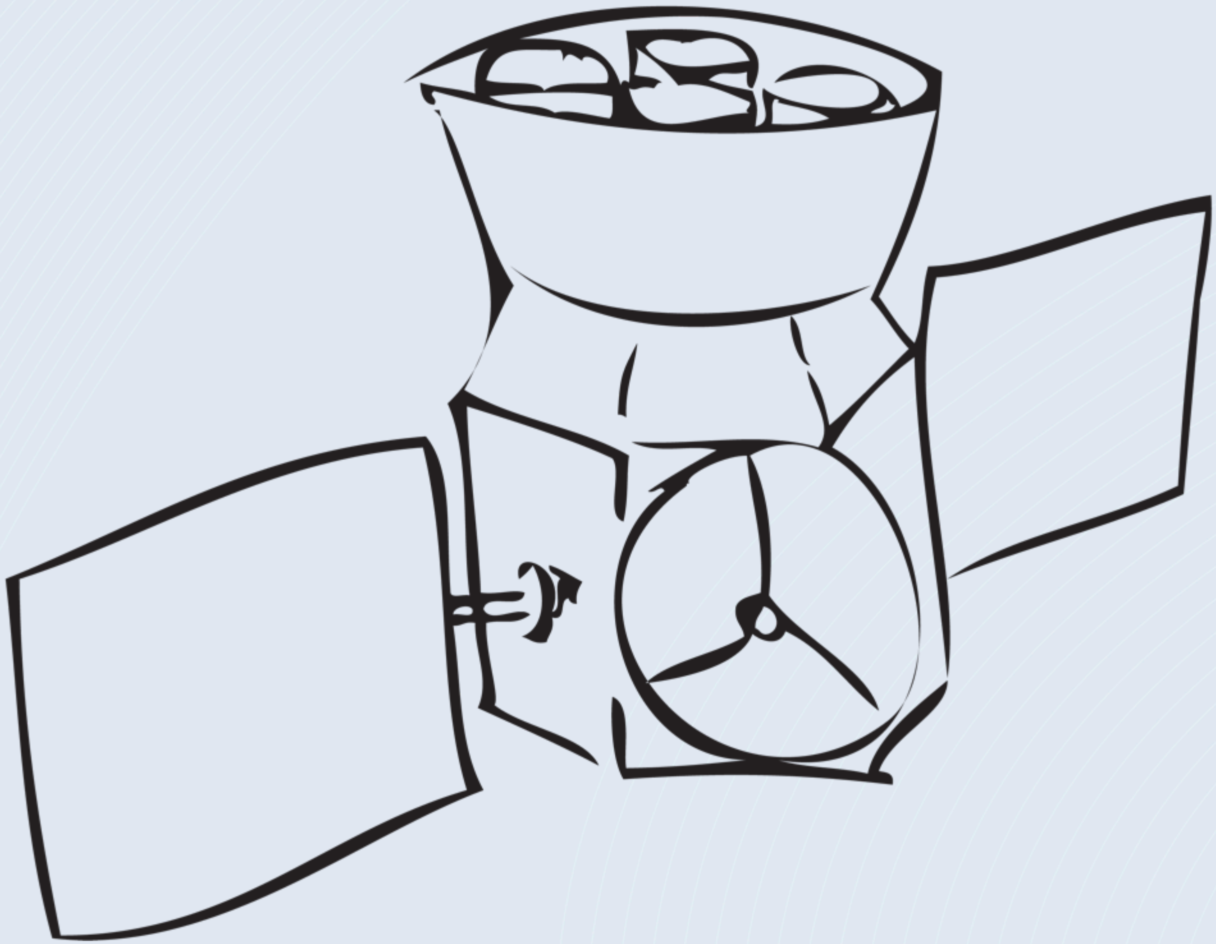
$1/R^2$ dependence means TESS stars are ~100 times brighter on average

Animation by Zach Berta-Thompson {units: 1pc ≈3 lt-yr}

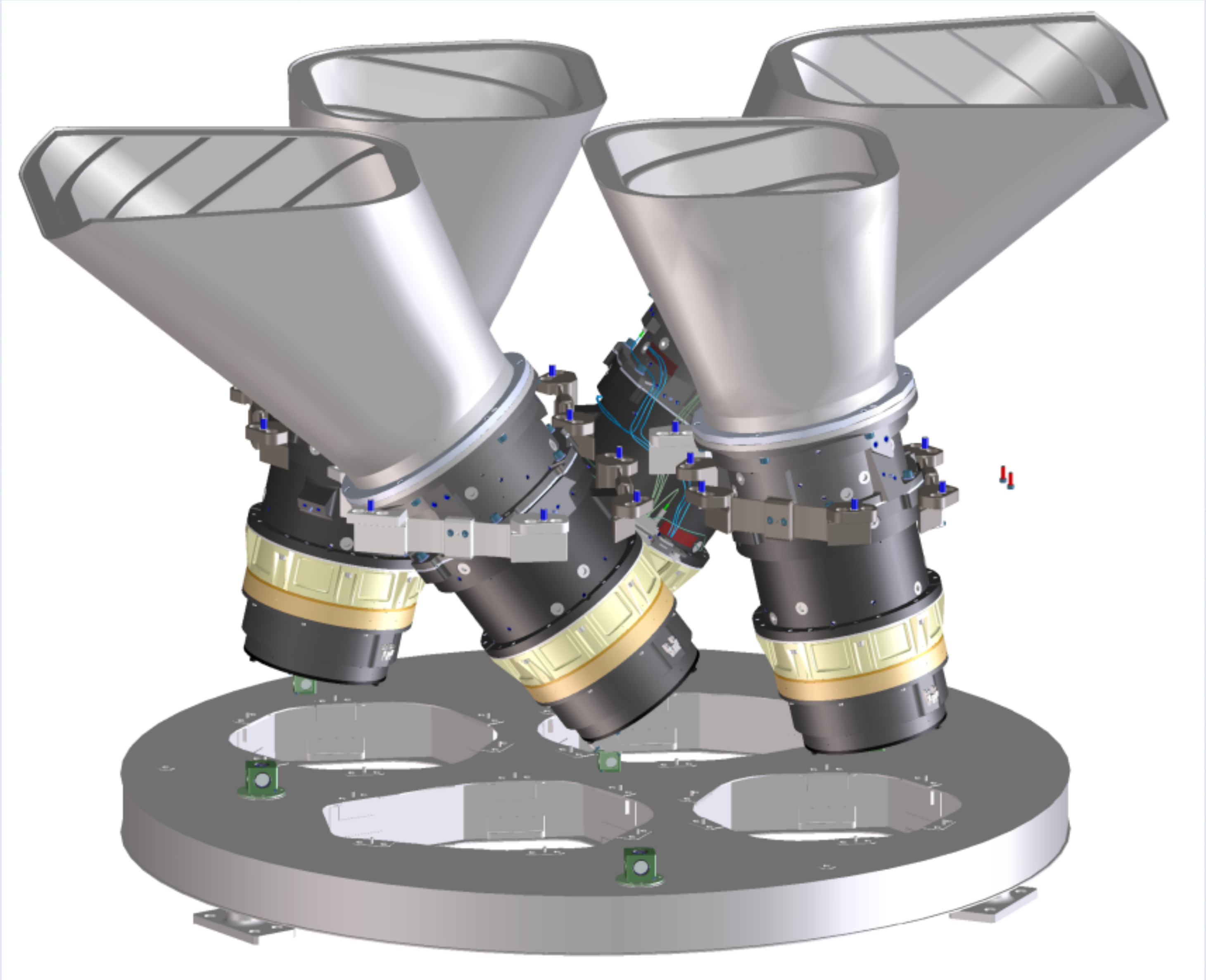


Transiting Exoplanets
Non-Kepler
Kepler
Predicted TESS
0h
September
21h
3h
18h
June
S
6h
December
15h
9h
12h
March
potentially
habitable
Animation by Zach Berta-Thompson {units: 1pc ≈3 lt-yr}

A brief tour of **TESS** CCD hardware



Layout of TESS Camera Array



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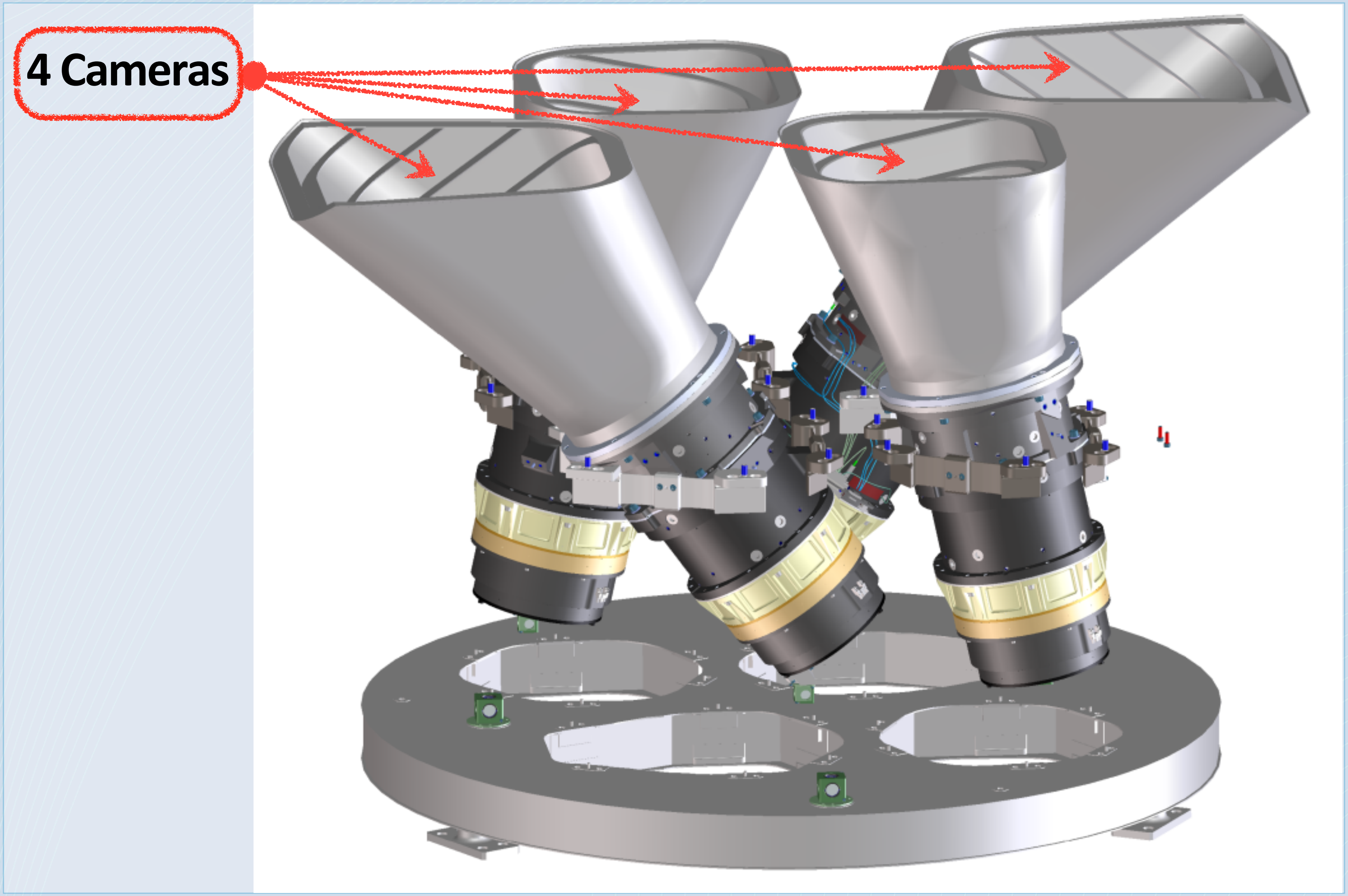

TESS Wide FOV CCD Camera

10.5 cm Aperture,
24° x 24° Field of View

Ricker et al. (2014)

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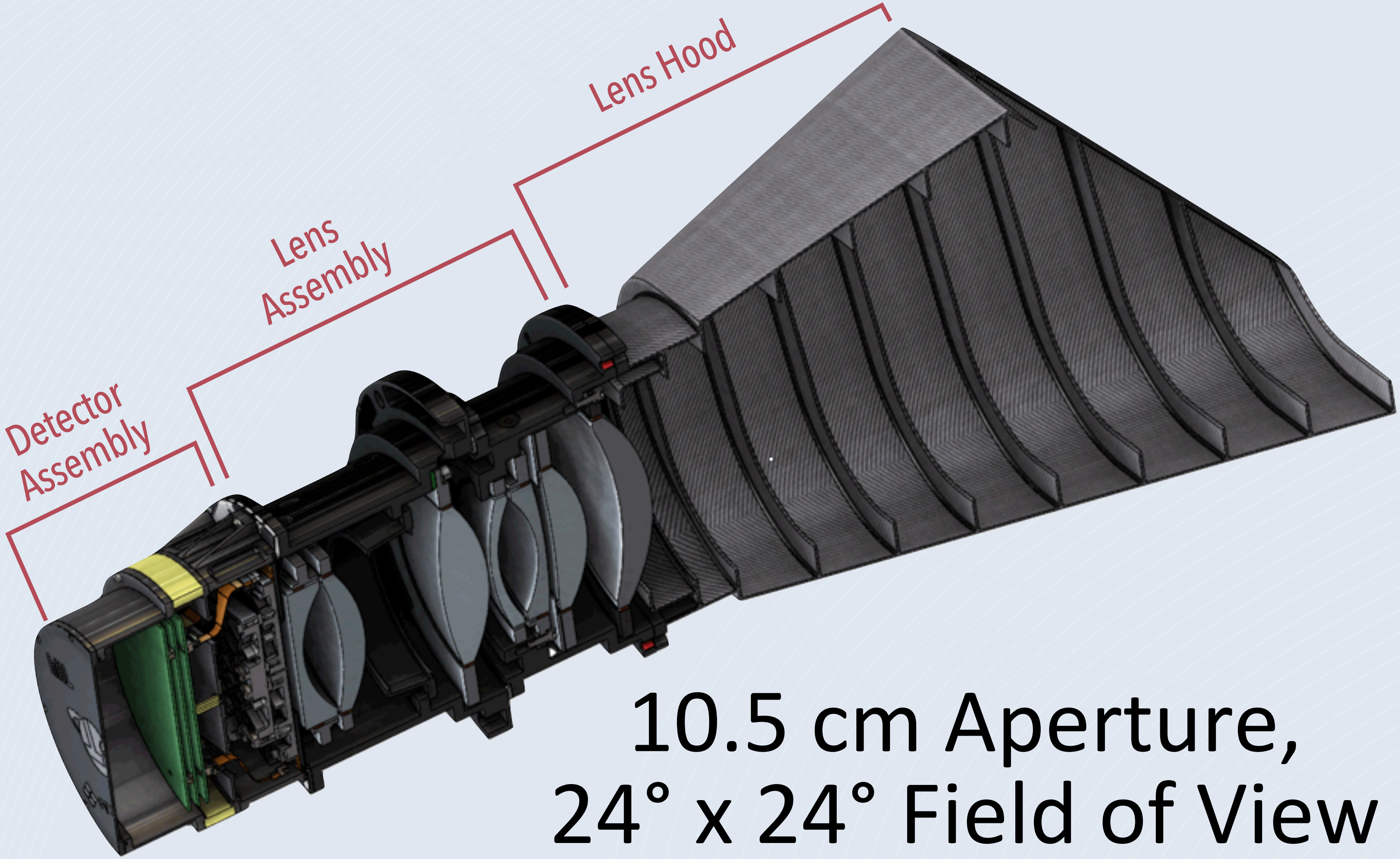

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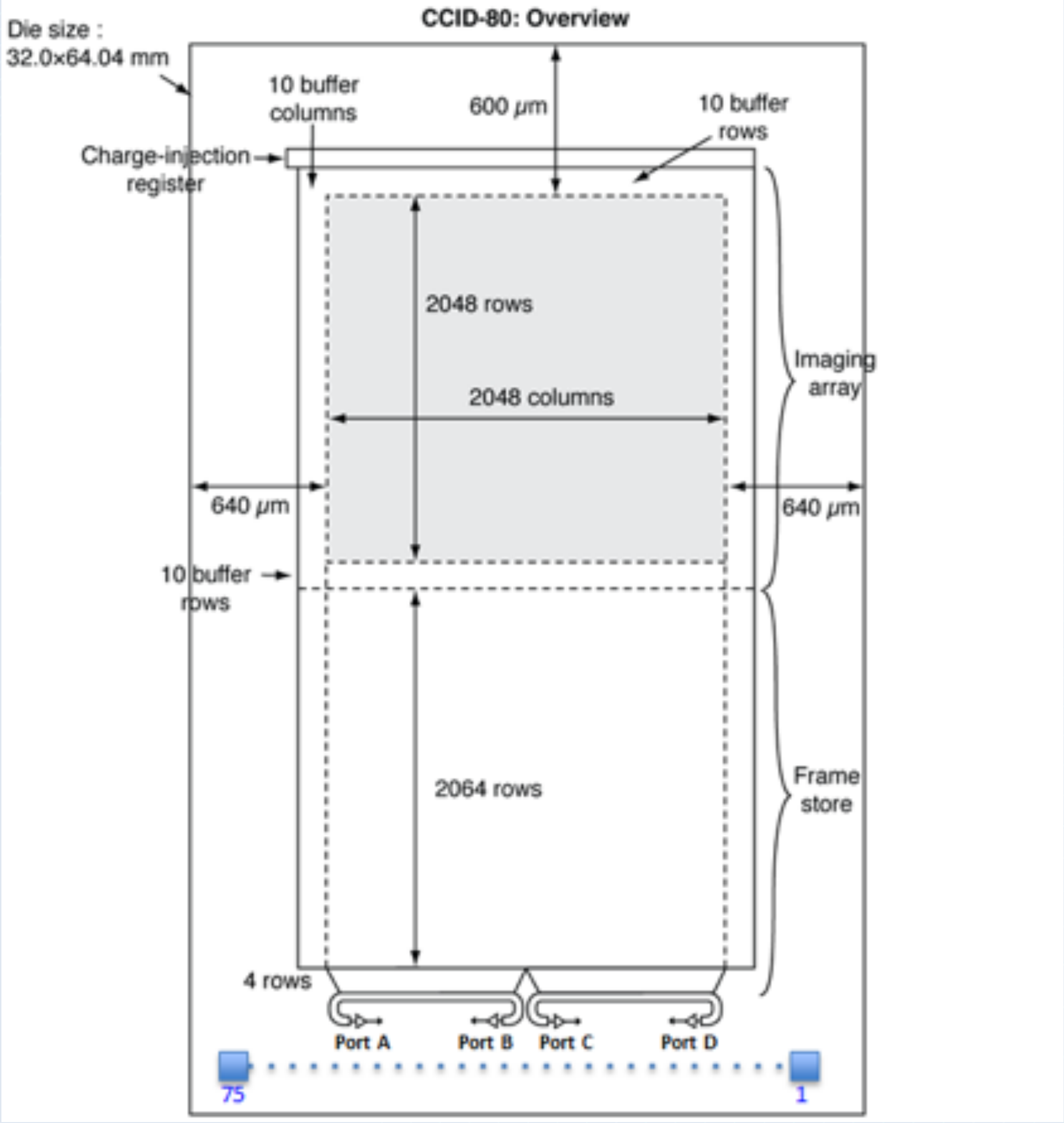
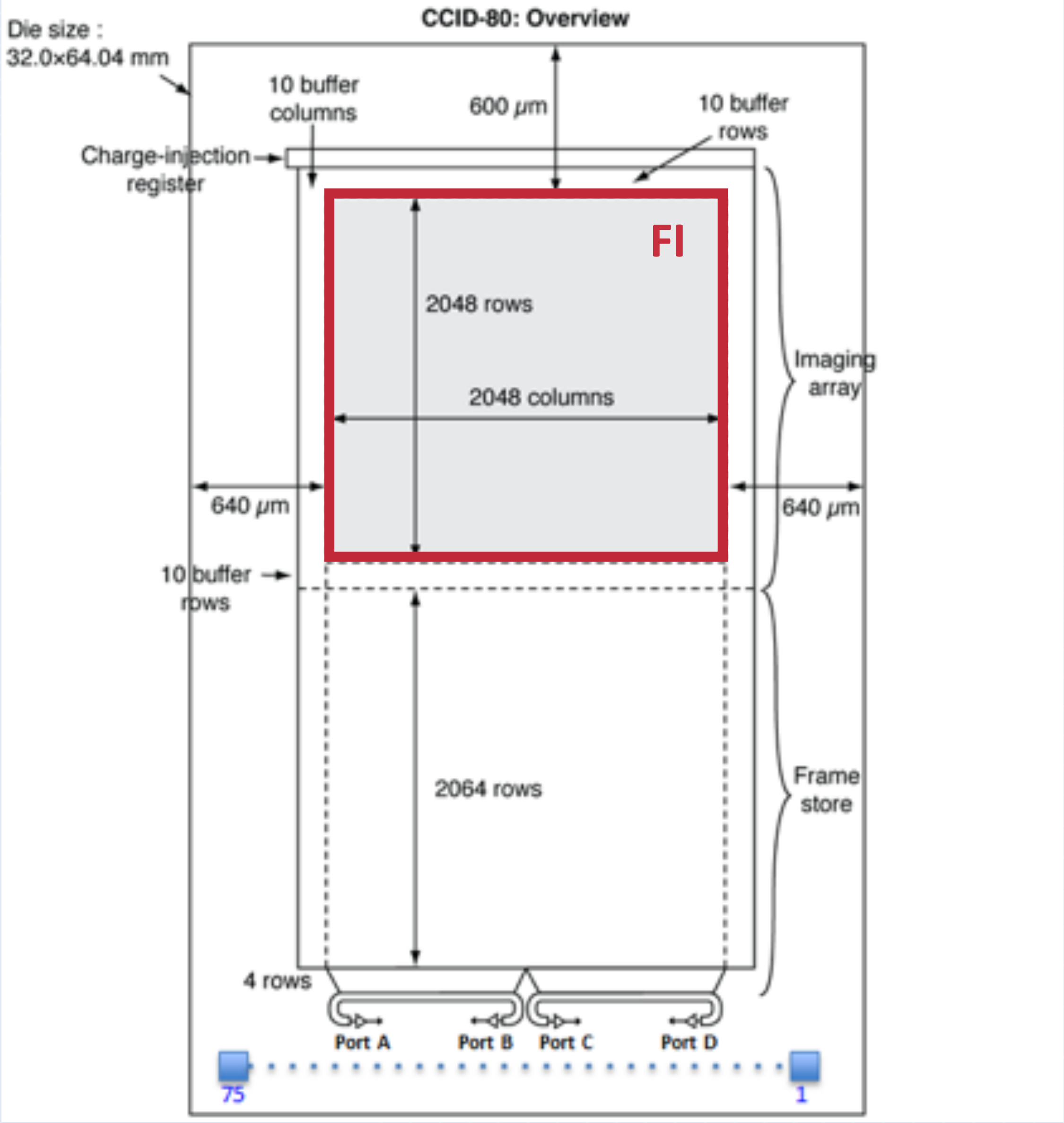
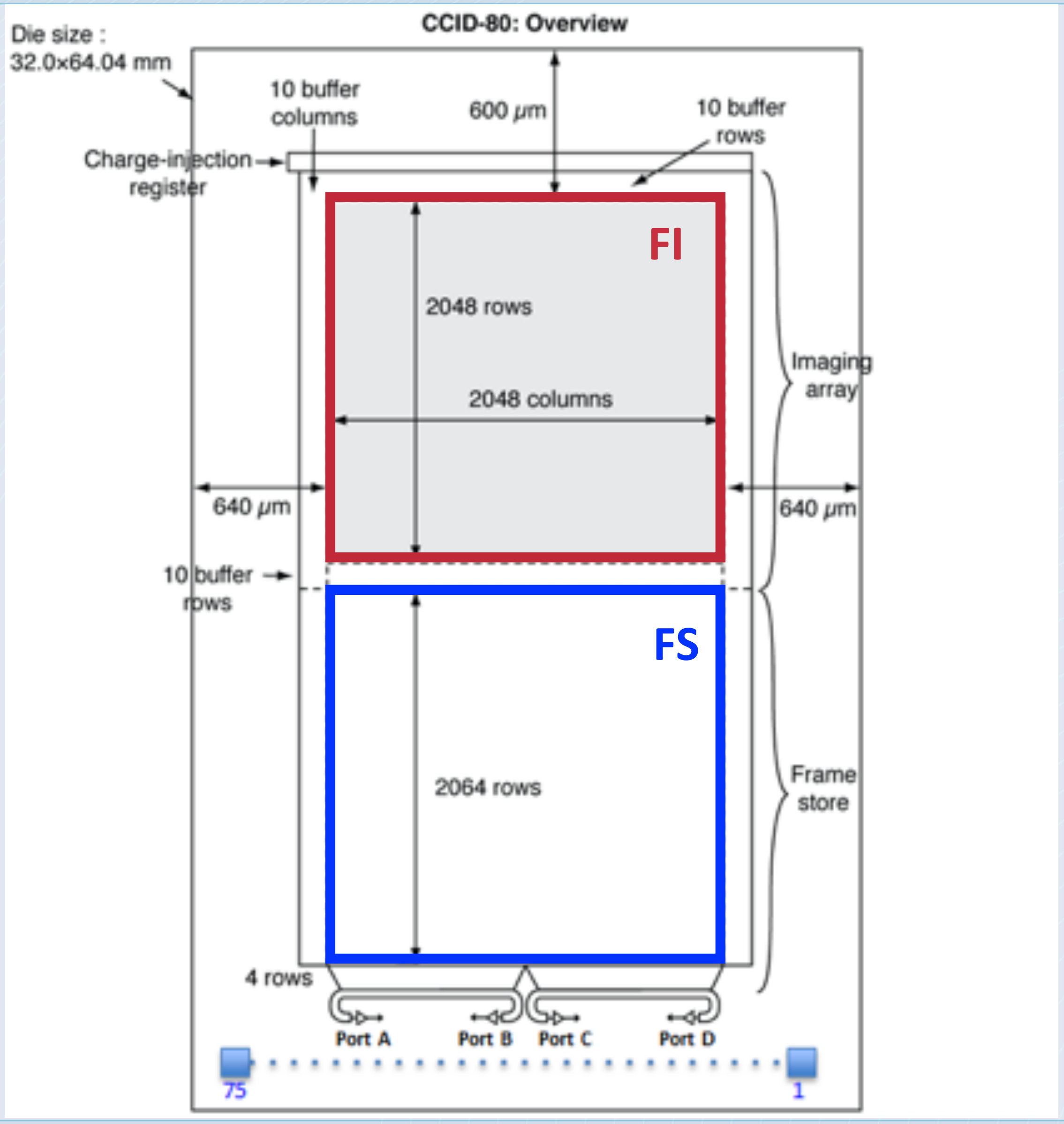
TESS CCID-80 Die Overview



TESS CCID-80 Die Overview



TESS CCID-80 Die Overview



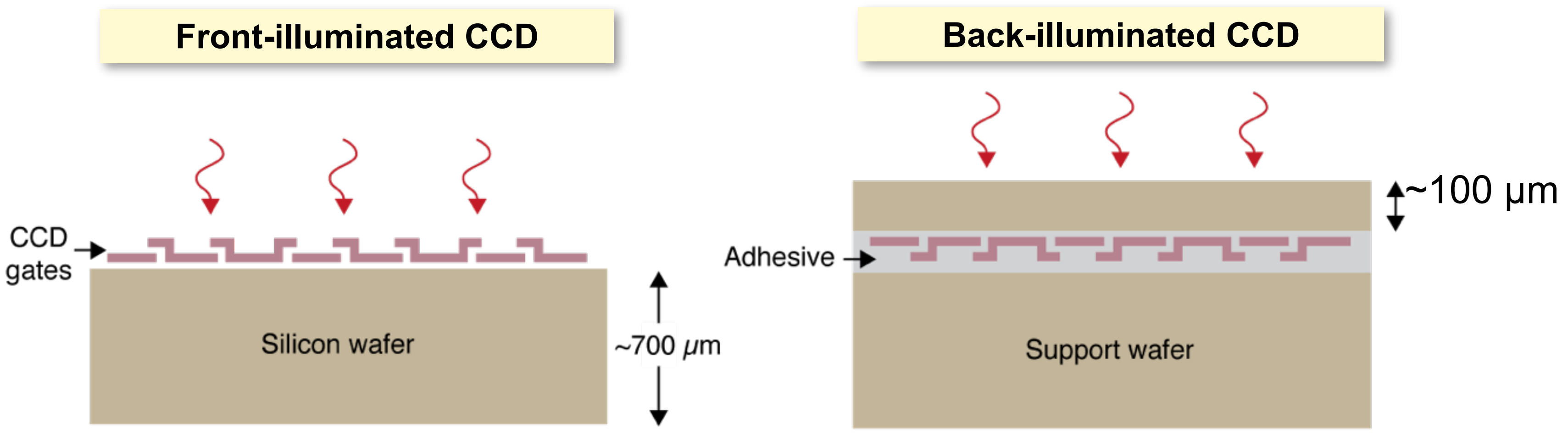
CCD Wafer Fabrication

- 200-mm wafer technology
  - High purity, float-zone silicon
  - Three poly, Two Metal
  - Stitched photolithography
- Back Illumination
  - Bonding, thinning to 100 micron
  - Back-surface passivation
  - Anti-reflection coating
  - Light shield
- On site Microelectronics Laboratory
  - 8,100 sq. ft. class-10 + 10,000 sq. ft. class-100
  - Trusted design and foundry certification
  - Broad application base
    - 90-nm CMOS
    - Single flux quantum electronics
    - 3D circuit stacking
    - Integrated photonics

Full Production Class CMOS Suite
Mix & Match and Stitching Lithography Capability

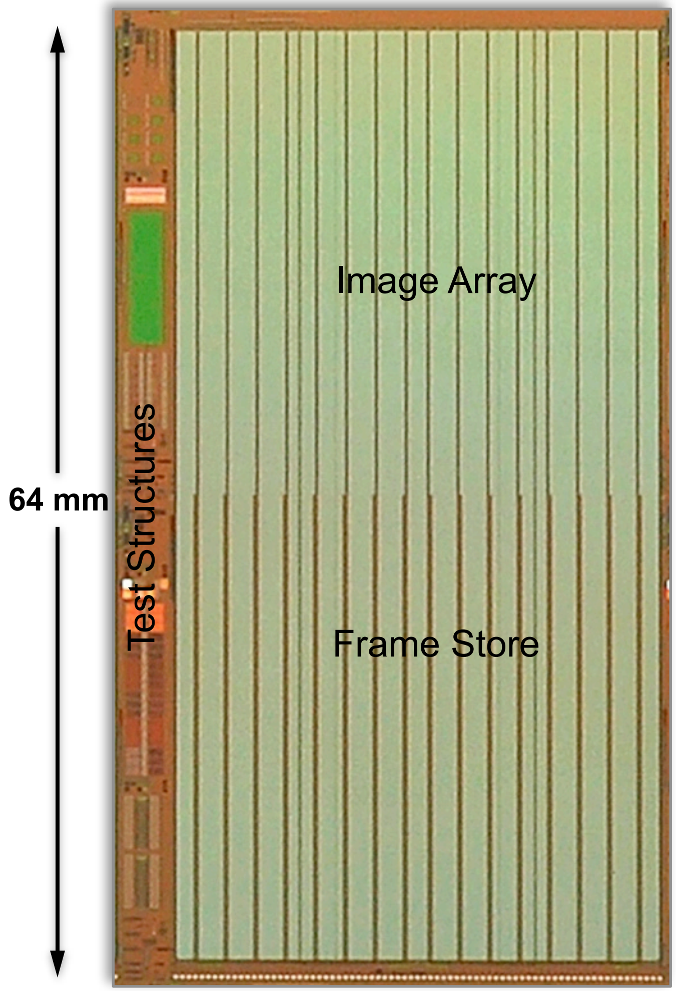
Two-Step CCD Fabrication Process

- Front illumination fabrication produces operational devices
- Subsequent back illumination fabrication steps include mounting and thinning
  - Dramatically improves device quantum efficiency
  - Reduces sub-pixel sensitivity variations



LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Completed CCID-80 Stages

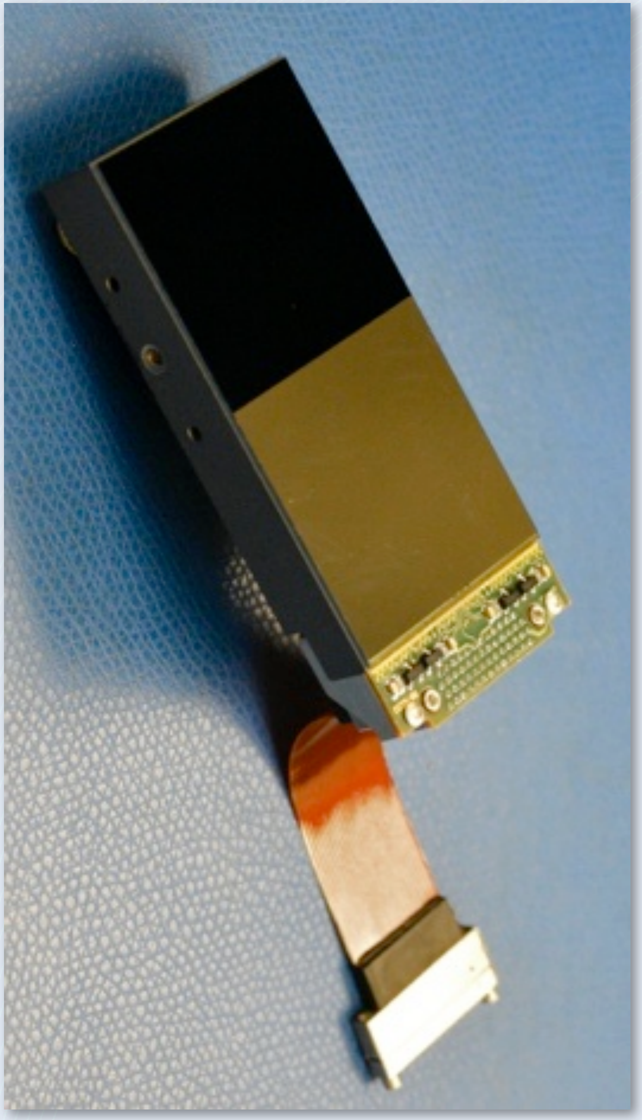


Front Illuminated Die Photo

Back Illuminated Die Photo

Packaged Part

Fully Depleted Back-Illuminated CCD for TESS: CCID-80



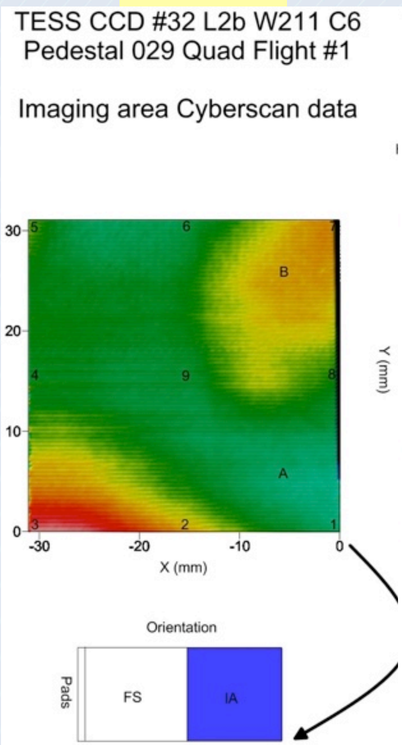
Parameter	Specification
Format	2048(H) x 2048(V) Frame Transfer
Physical Pixels	2048 x 4132 [32 x 64 mm die]
Pixel Size	15µm x 15µm
Output Ports	Single Stage MOSFET – 4 per CCD
Charge Injection	Three-phase CI register at top
Silicon Thickness	100µm high resistivity (>5 kohm-cm)
Depletion Control	Detector bias
Package Type	3-side abuttable
Charge Handling	> 150ke-
Noise	< 20e- with FPE @ 625kHz
QE	> 50% @ 950nm
Quantity	> 26 flight grade devices

CCID-80 Back-Illuminated Test Results

	Performance	Specification	Achieved
✔	**Full Well Capacity**	> 150,000 e- (goal)	**> 200,000 e-**
✔	**Conservation of Bloomed Charge**	Best Effort	**~ 100x full well**
✔	**Conversion Gain**	< 10 µV/e-	**8 µV/e-**
✔	**Read Noise @ 625 kHz**	< 20 e-	**< 10 e-**
✔	**Dark Current @ -30°C**	< 8 e-/pix/s	**< 2.5 e-/pix/s**
✔	**Device Thickness**	100 µm (-10/+15µm)	**95 – 115 µm**
✔	**Depletion-depth control**	Substrate bias	**Functional**
✔	**Targeted Spectral Range**	600-1000 nm	**70% @ 950 nm**
✔	**Flight Quantity Needed**	26	**>70** **Candidates for packaging**

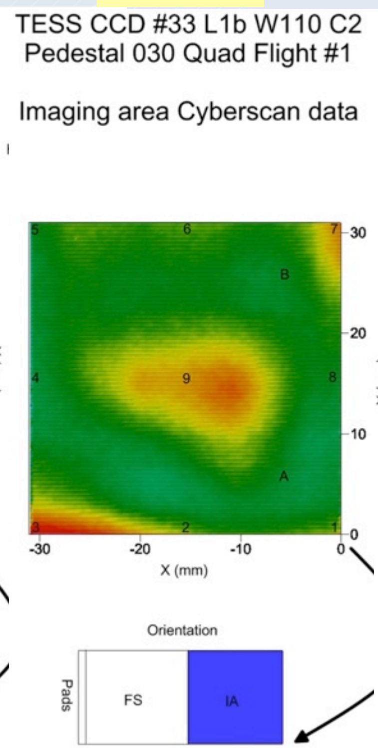
TESS CCD Flatness: Meets Requirements

FLT1-SN5-1



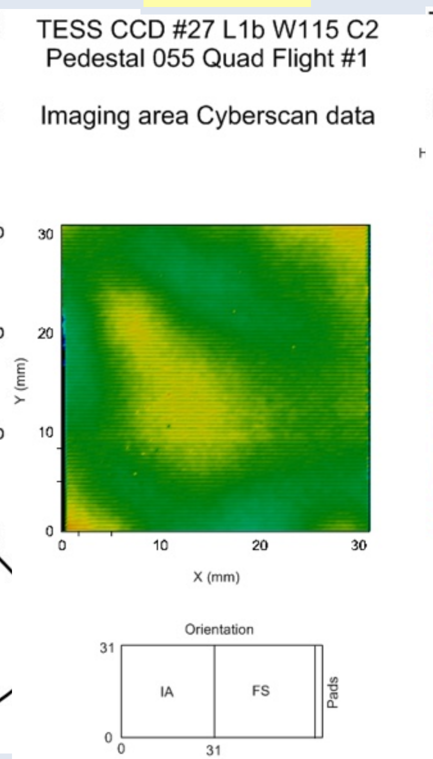
FC05-32-2b-211-C6
7µm Range

FLT1-SN5-2



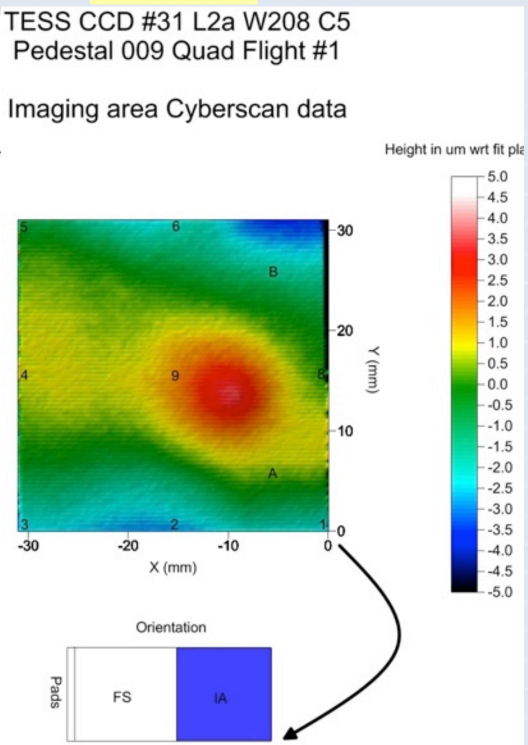
FC06-33-1b-110-C2
5µm Range

FLT1-SN5-3



FC01-27-1b-115-C2
4µm Range

FLT1-SN5-4



FC04-31-2a-208-C5
8µm Range

TESS Focal Plane Array Flat Field

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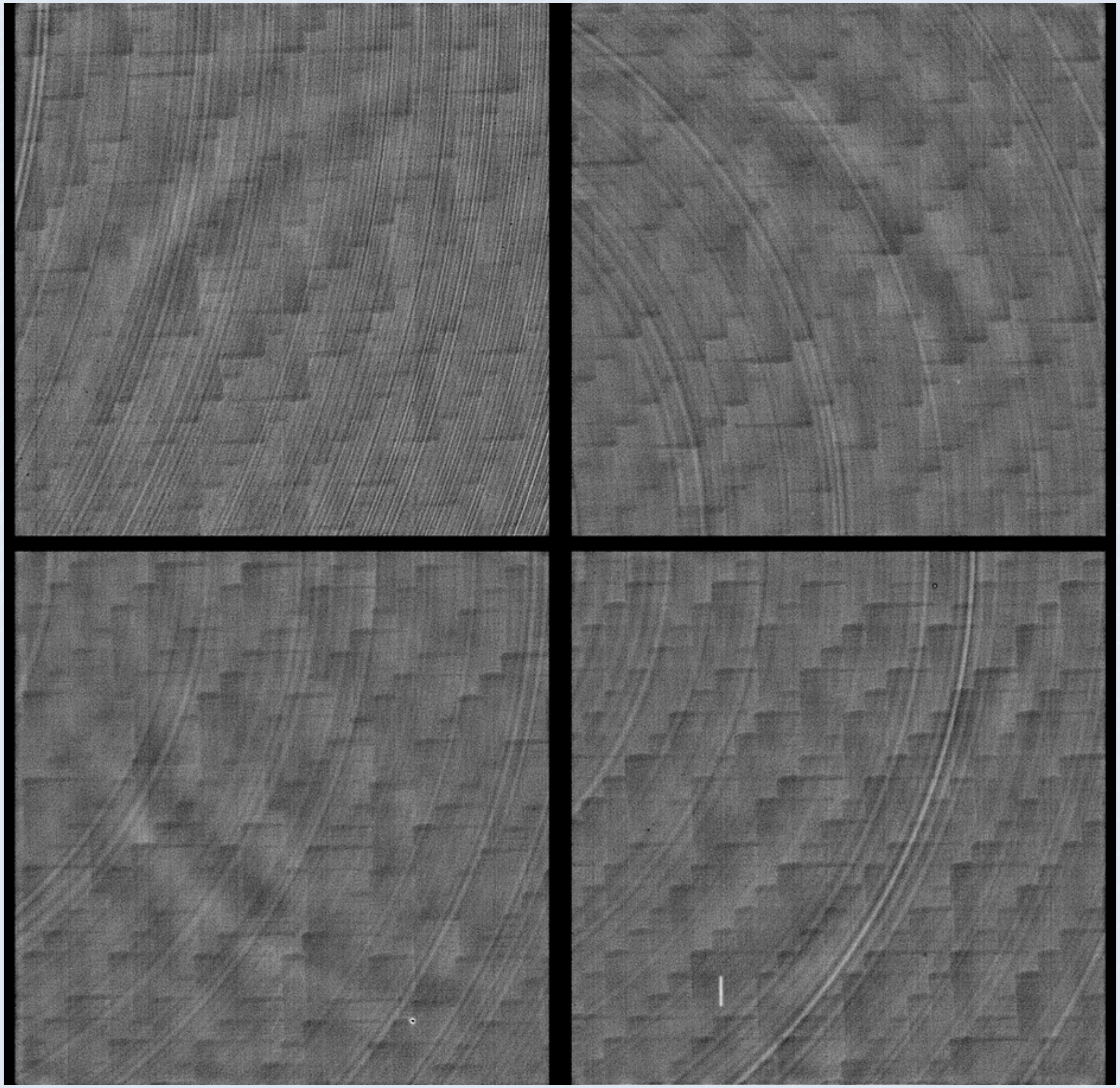

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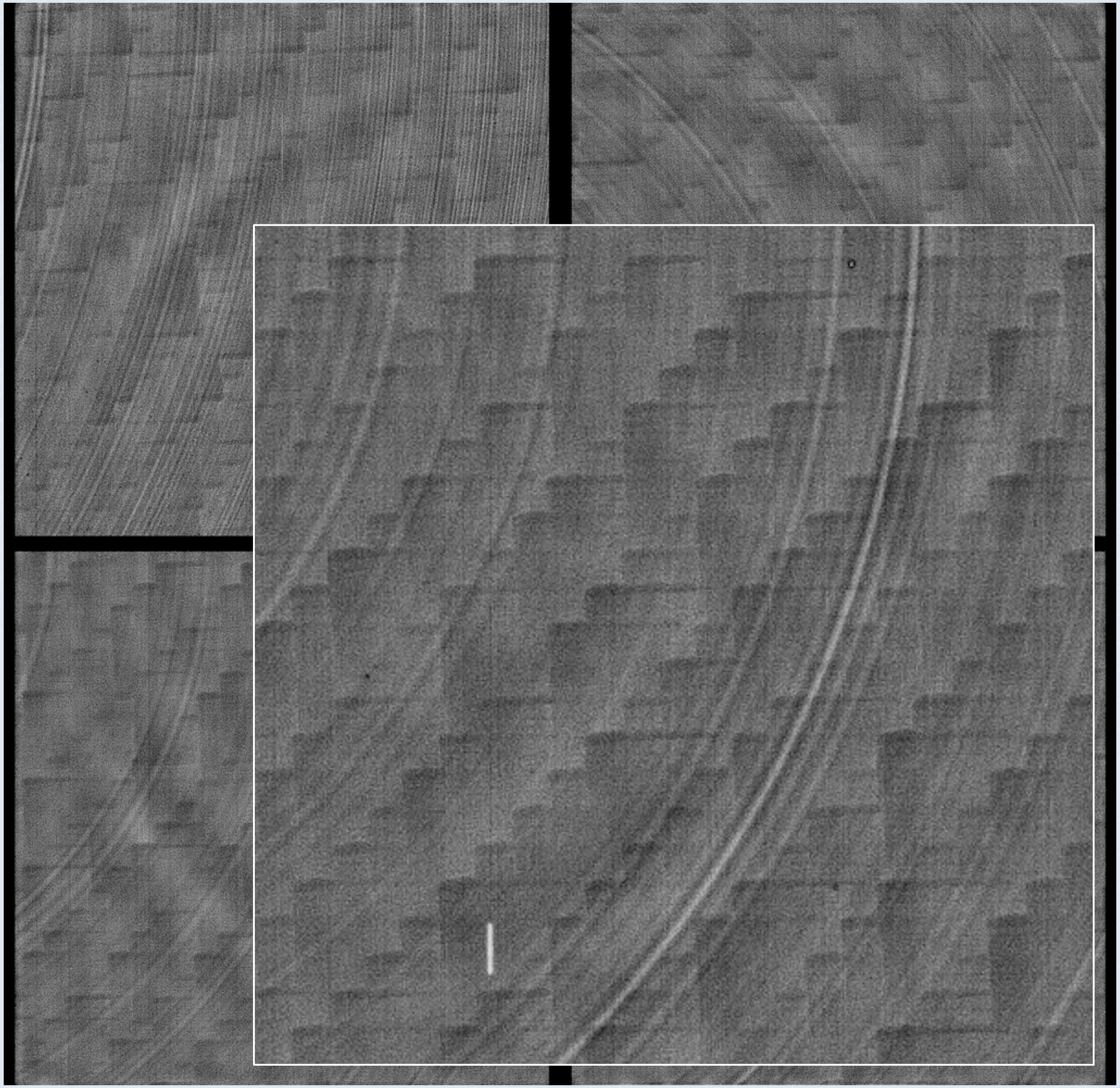

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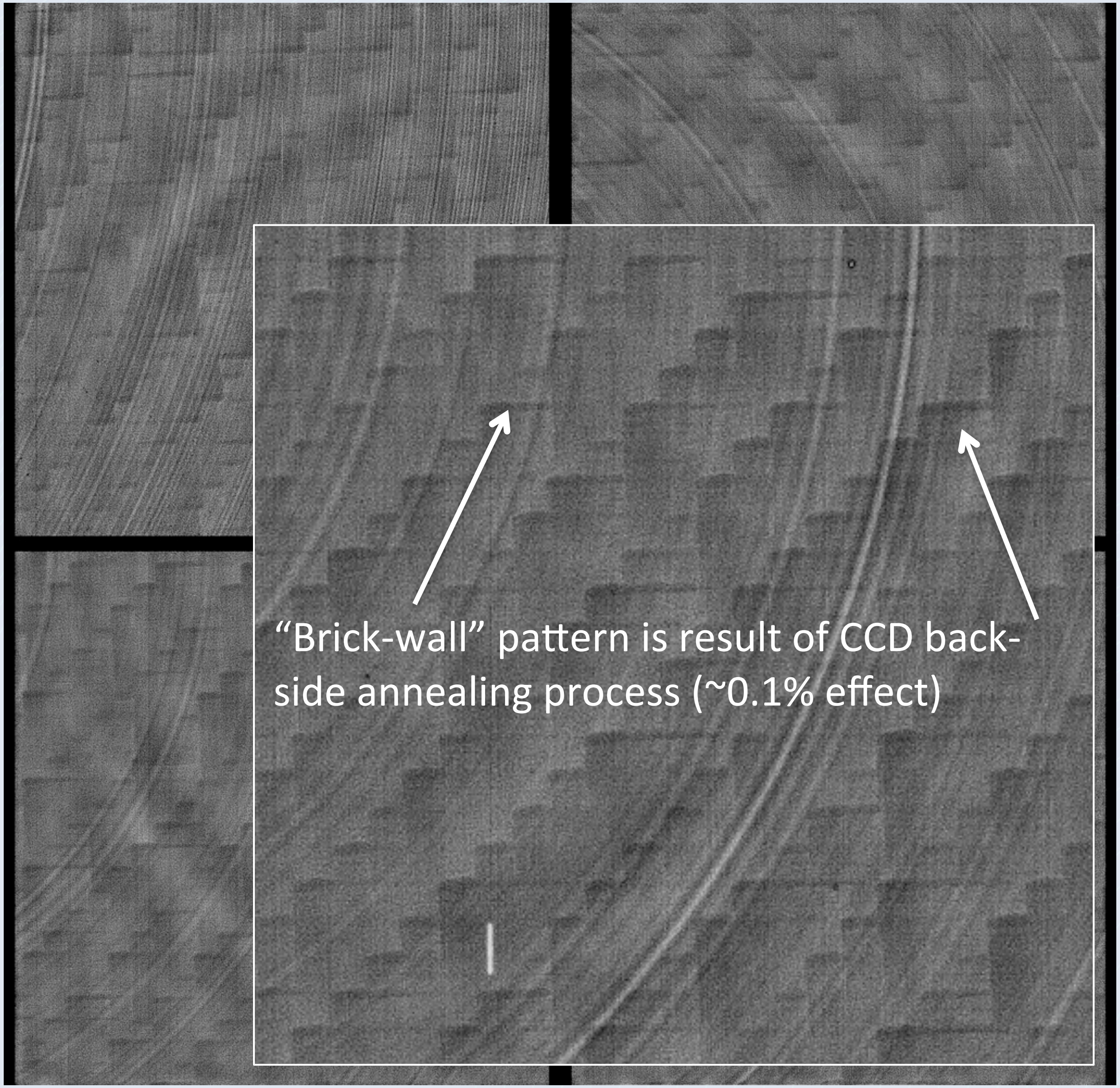

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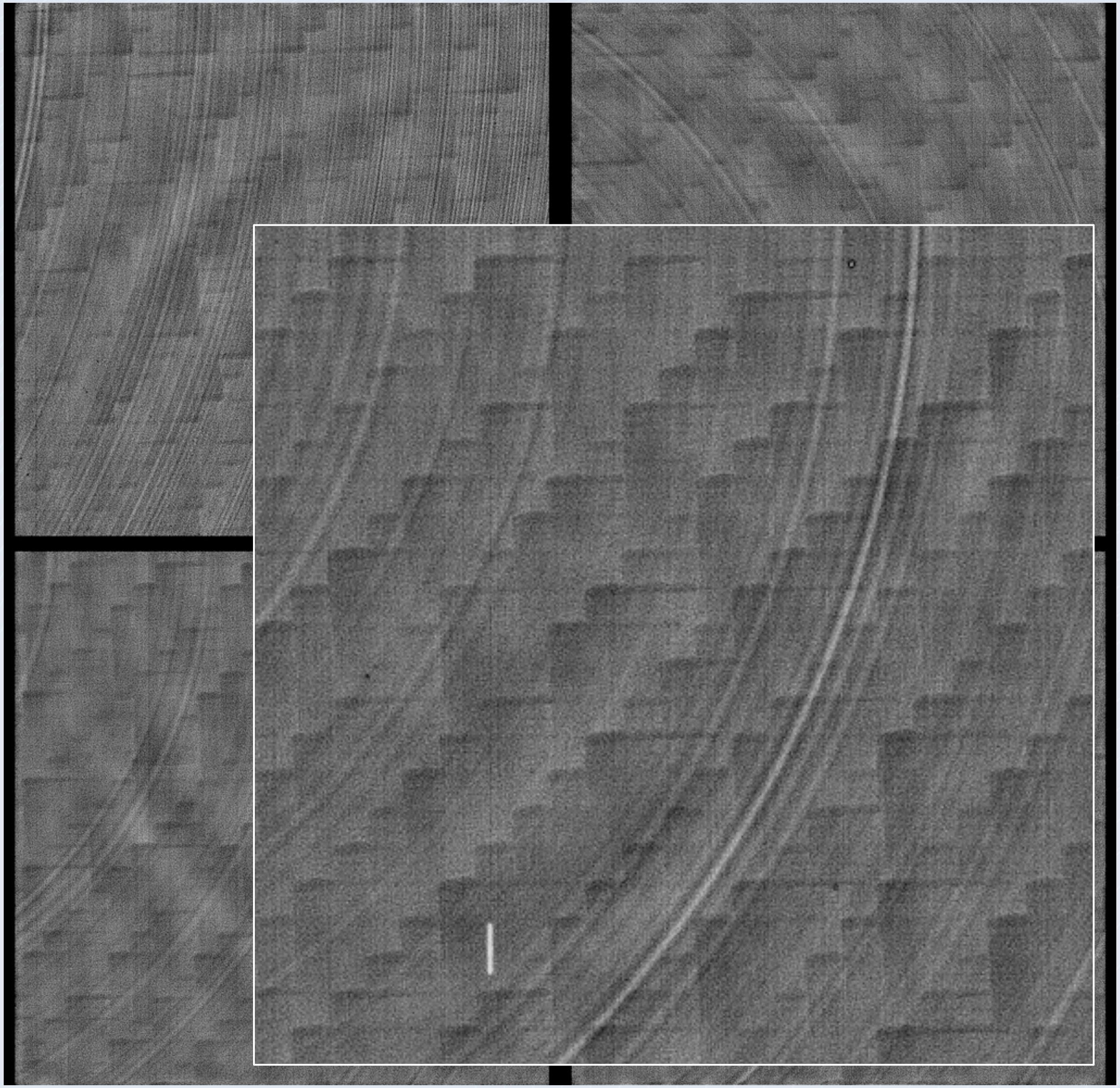

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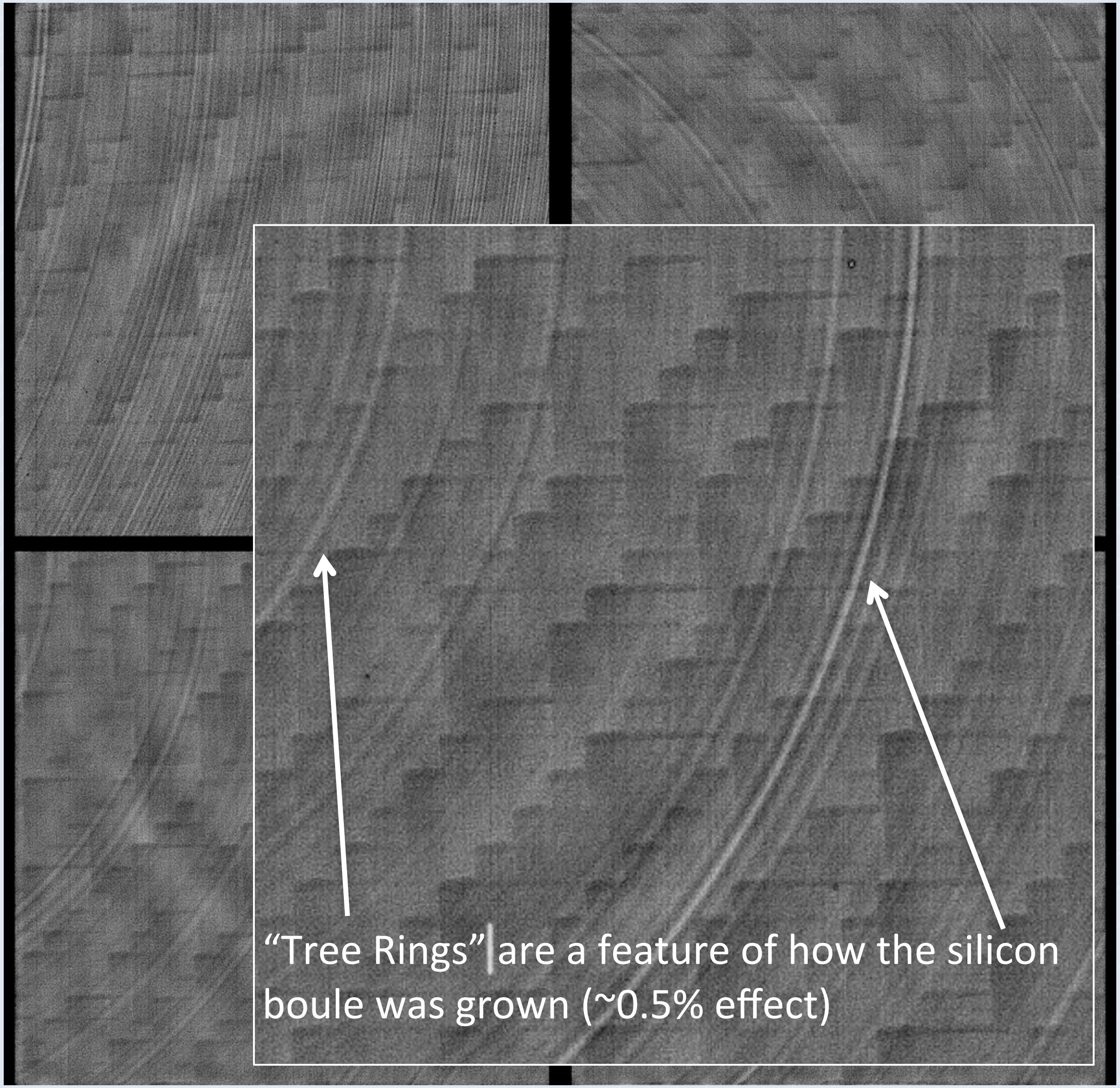

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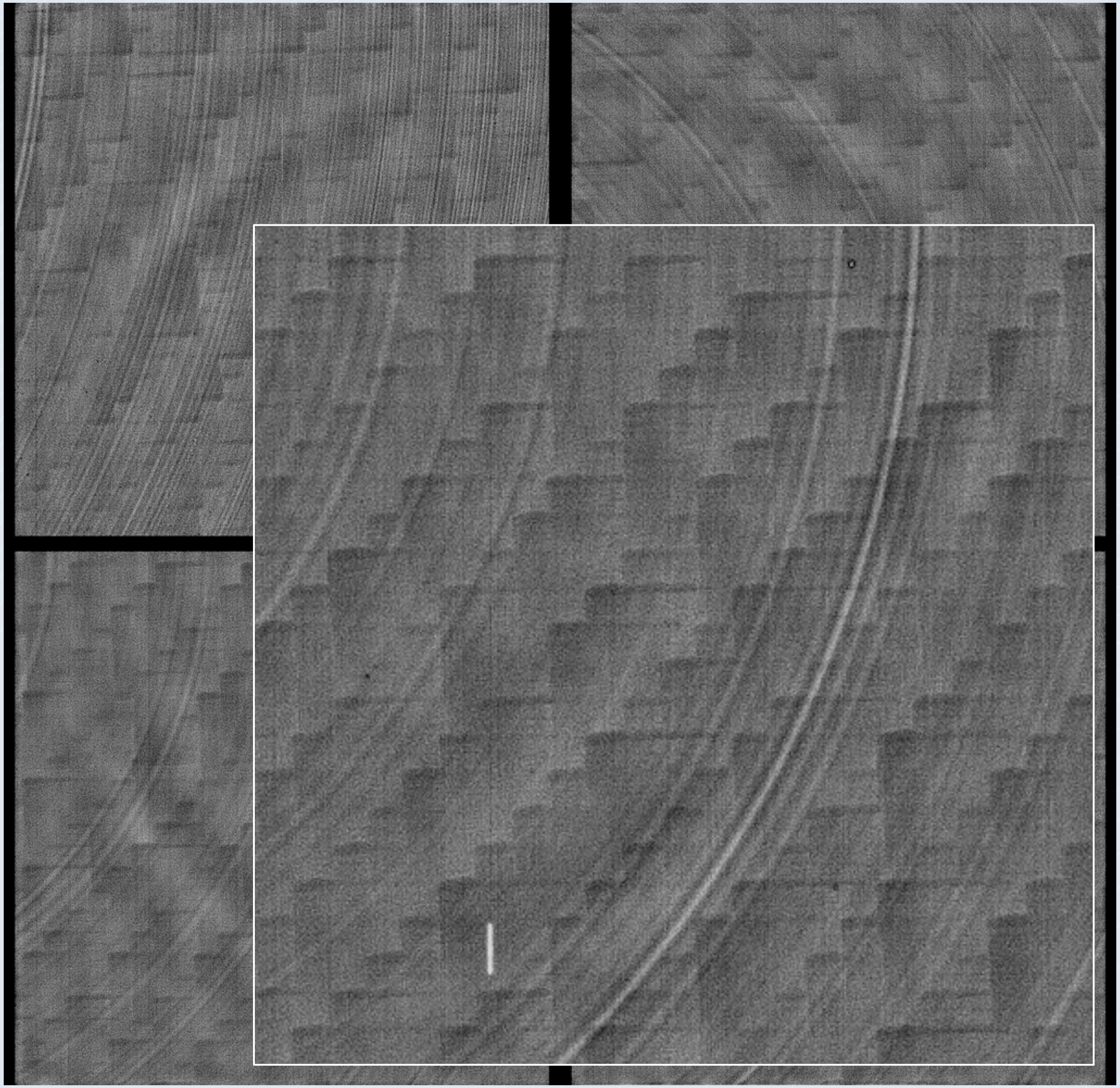

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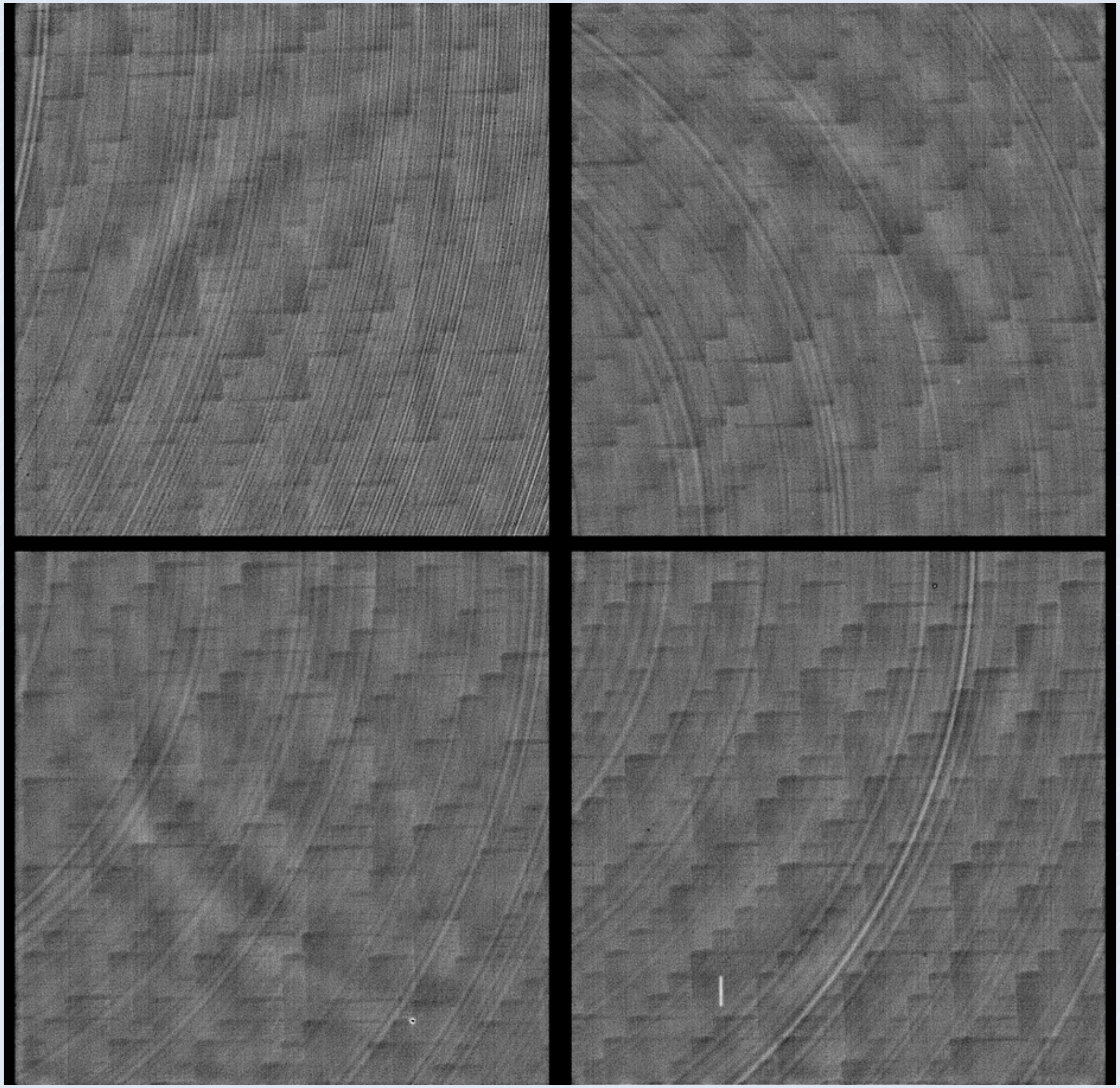

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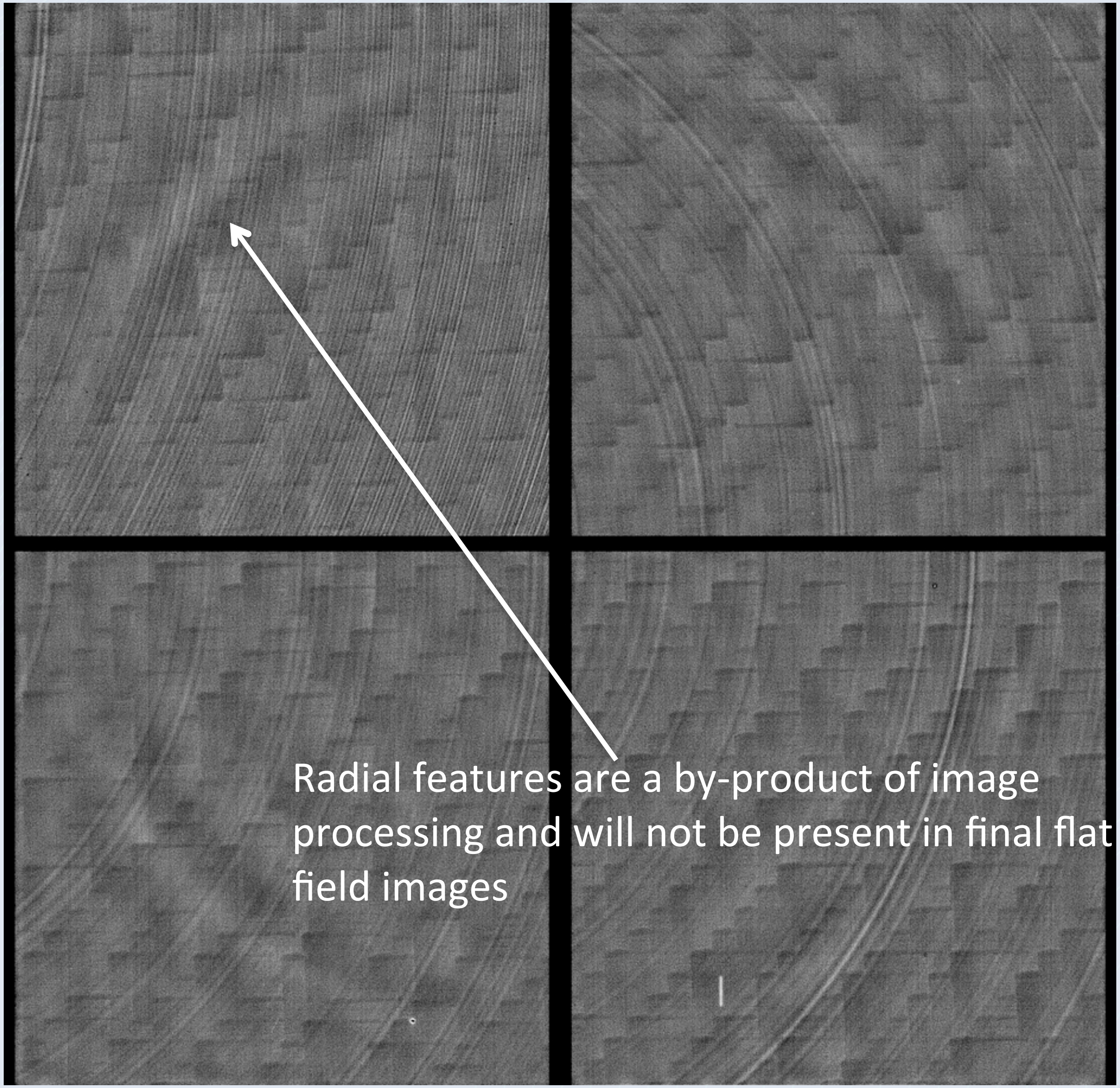
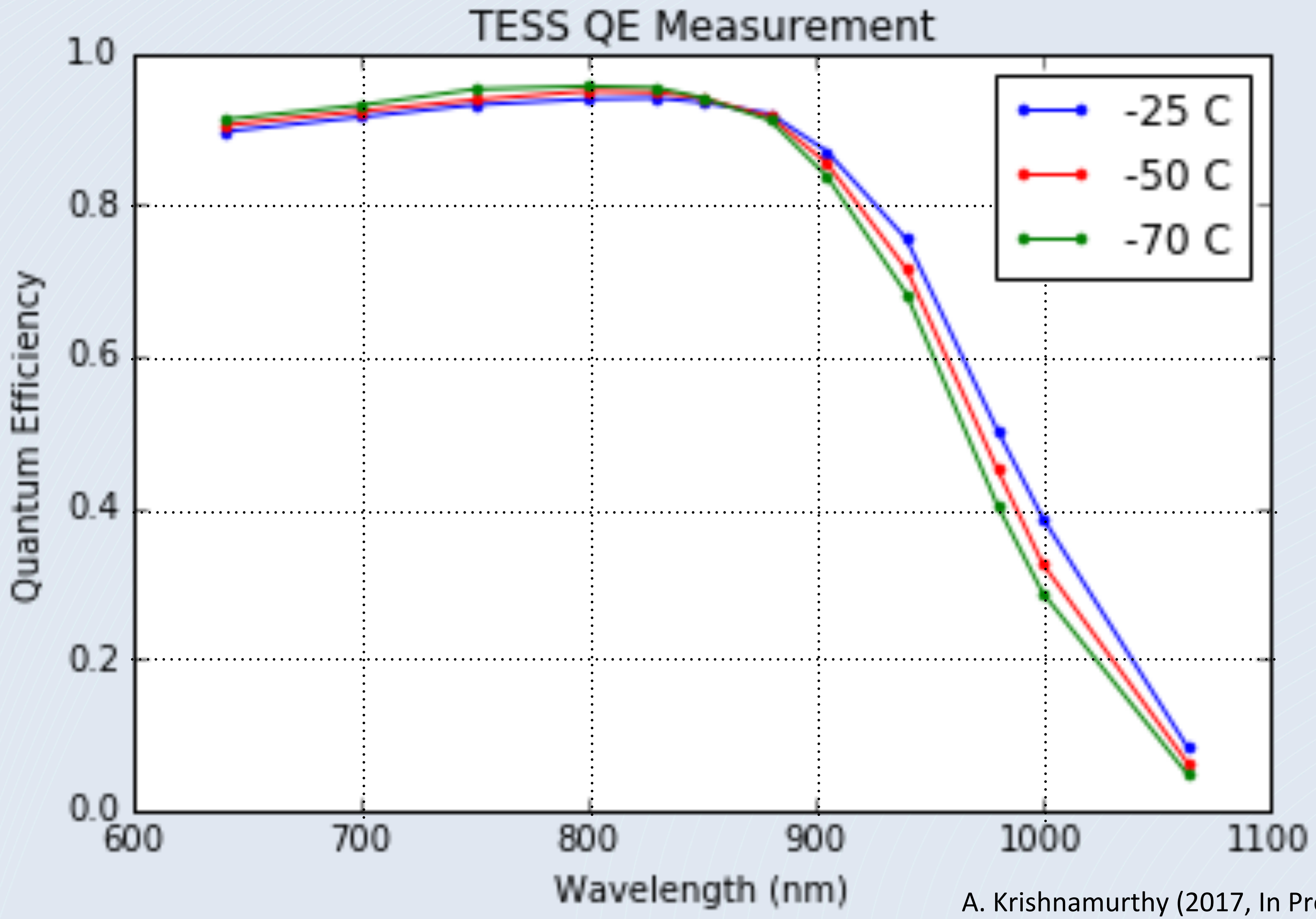


TESS CCID-80 QE Measurements



A. Krishnamurthy (2017, In Prep)

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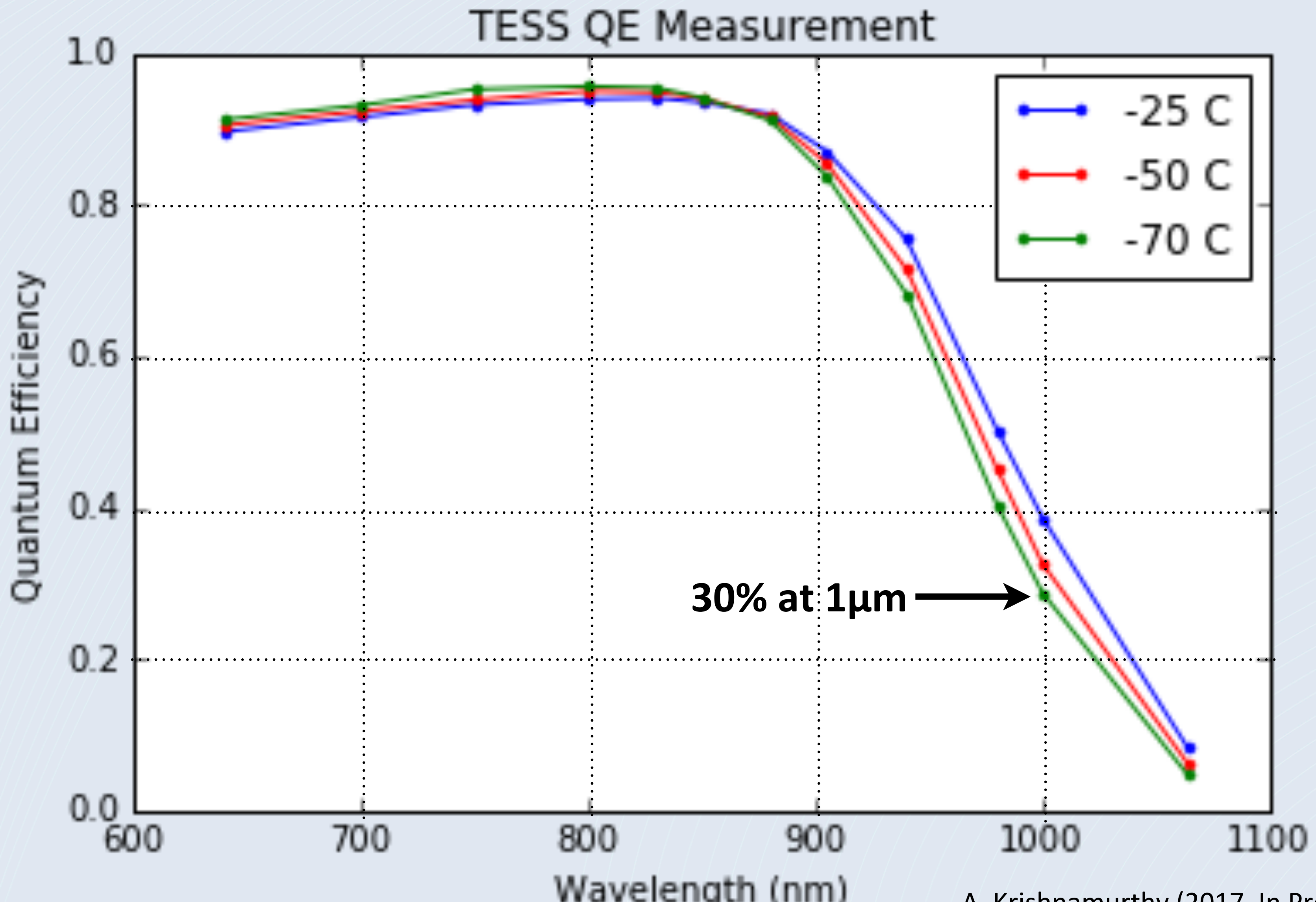

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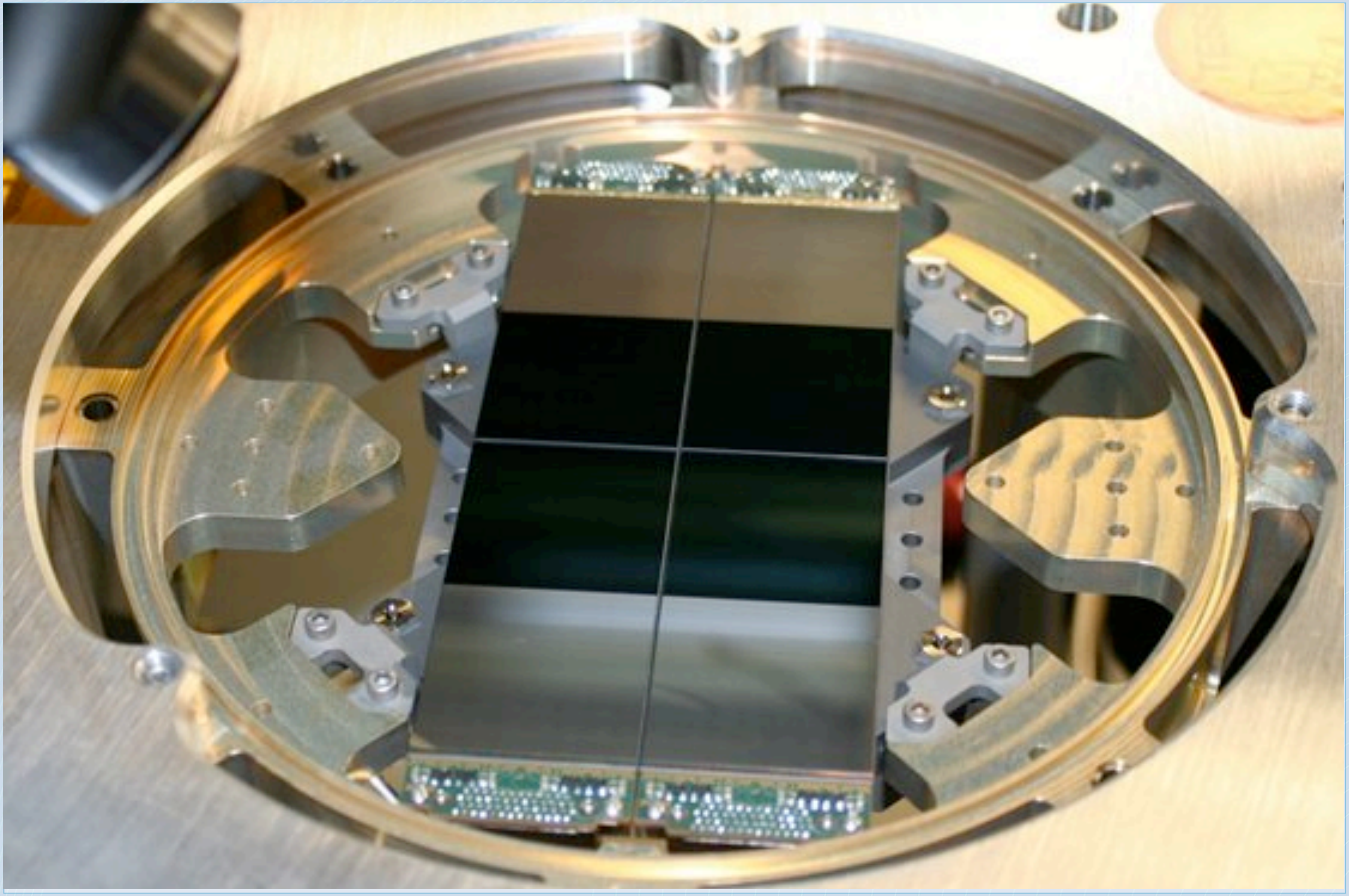
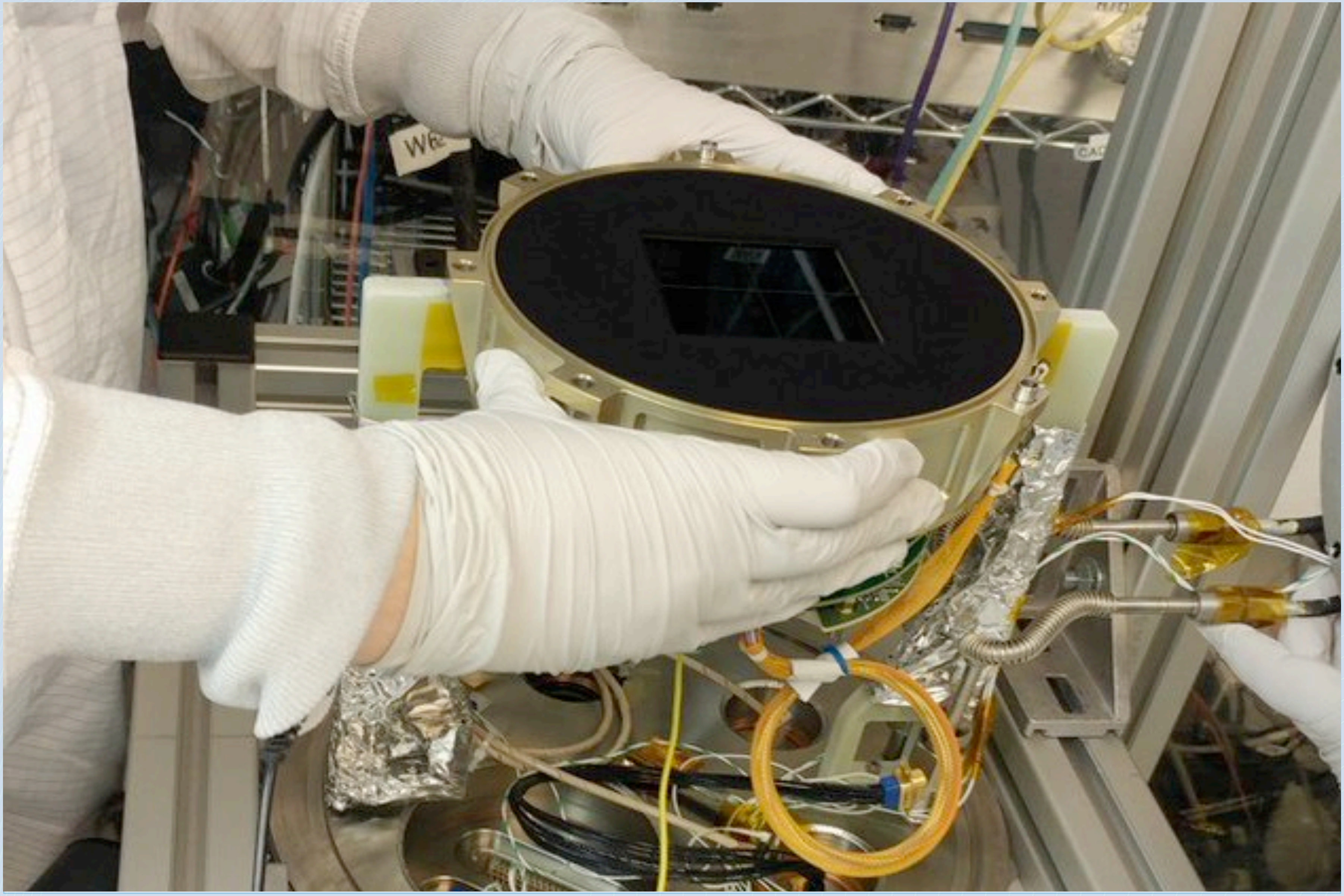
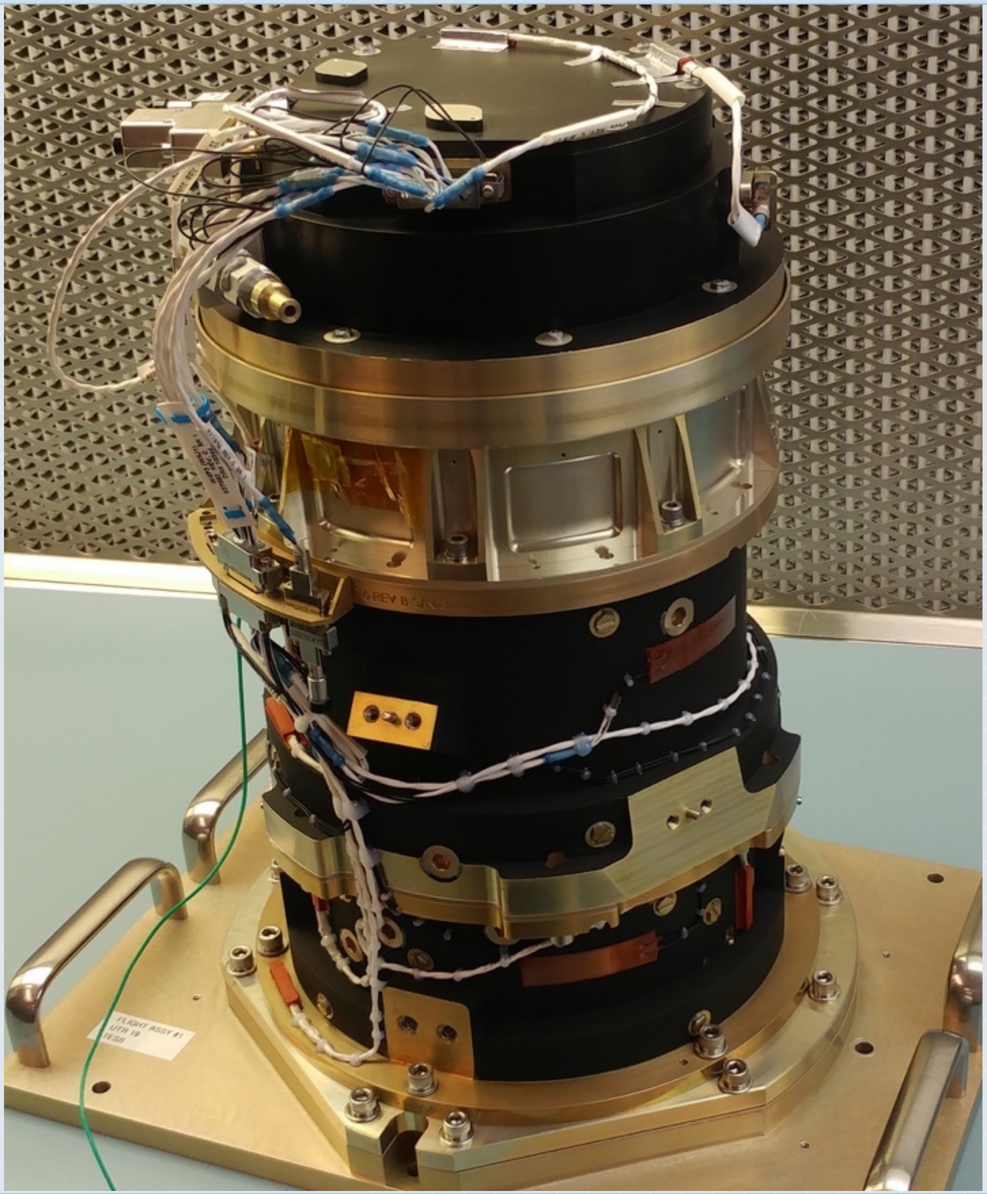
TESS CCD Focal Plane Array During Final Inspection



TESS Flight Focal Plane Array #2 in Test at MIT



TESS Flight Camera 1 Prep'd for Thermal Vac Tests



TESS Sky Mapping Strategy

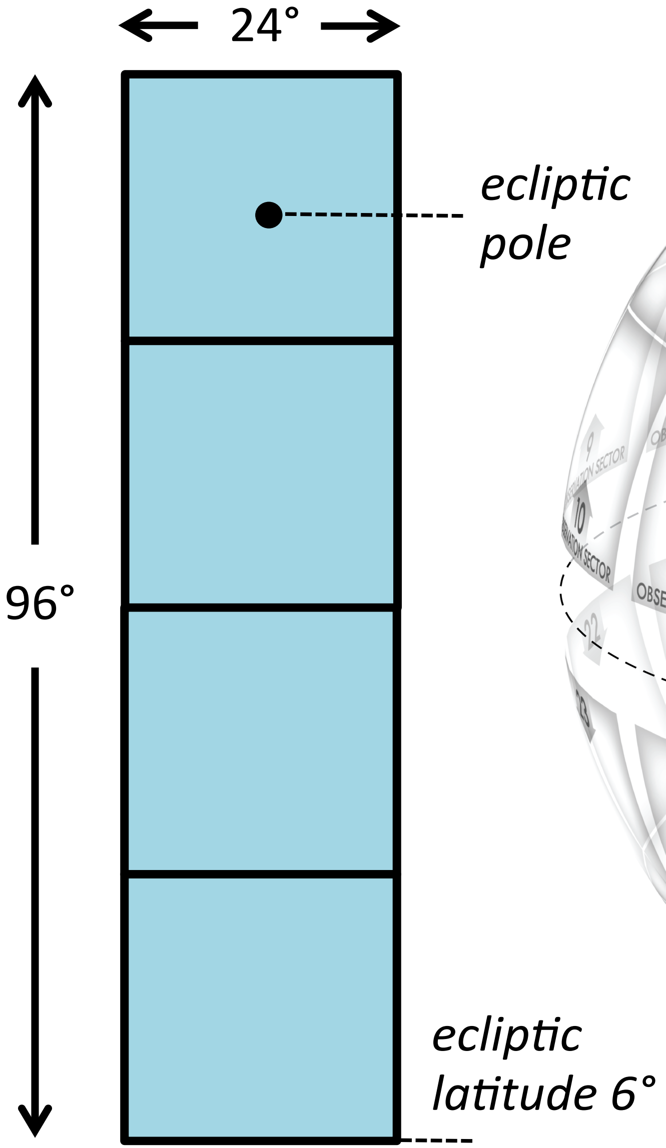
http://www.youtube.com/watch?v=mpViVEO-ymc

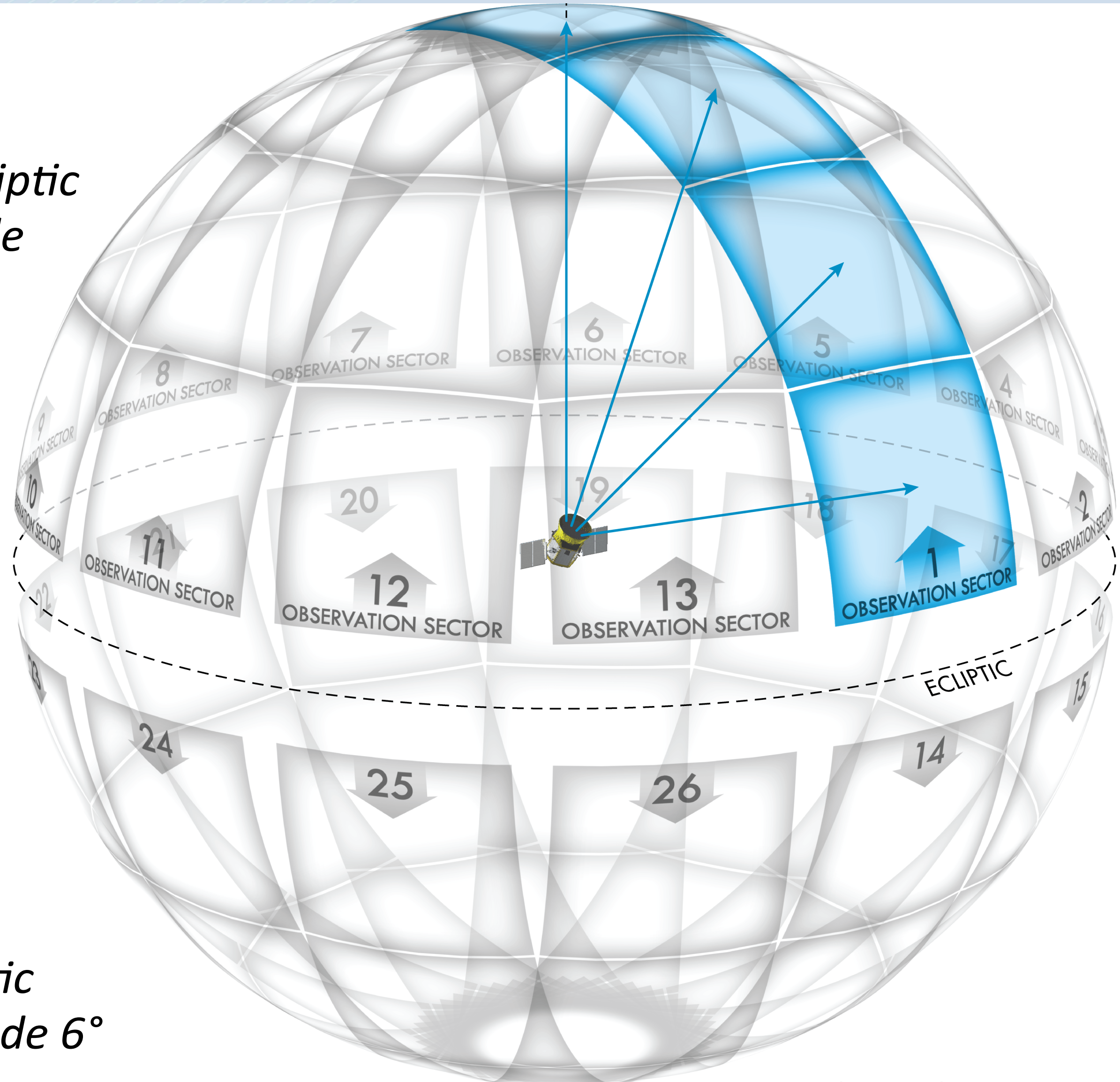
TESS

TRANSITING EXOPLANET SURVEY SATELLITE

DISCOVERING NEW EARTHS AND SUPER-EARTHS
IN THE SOLAR NEIGHBORHOOD

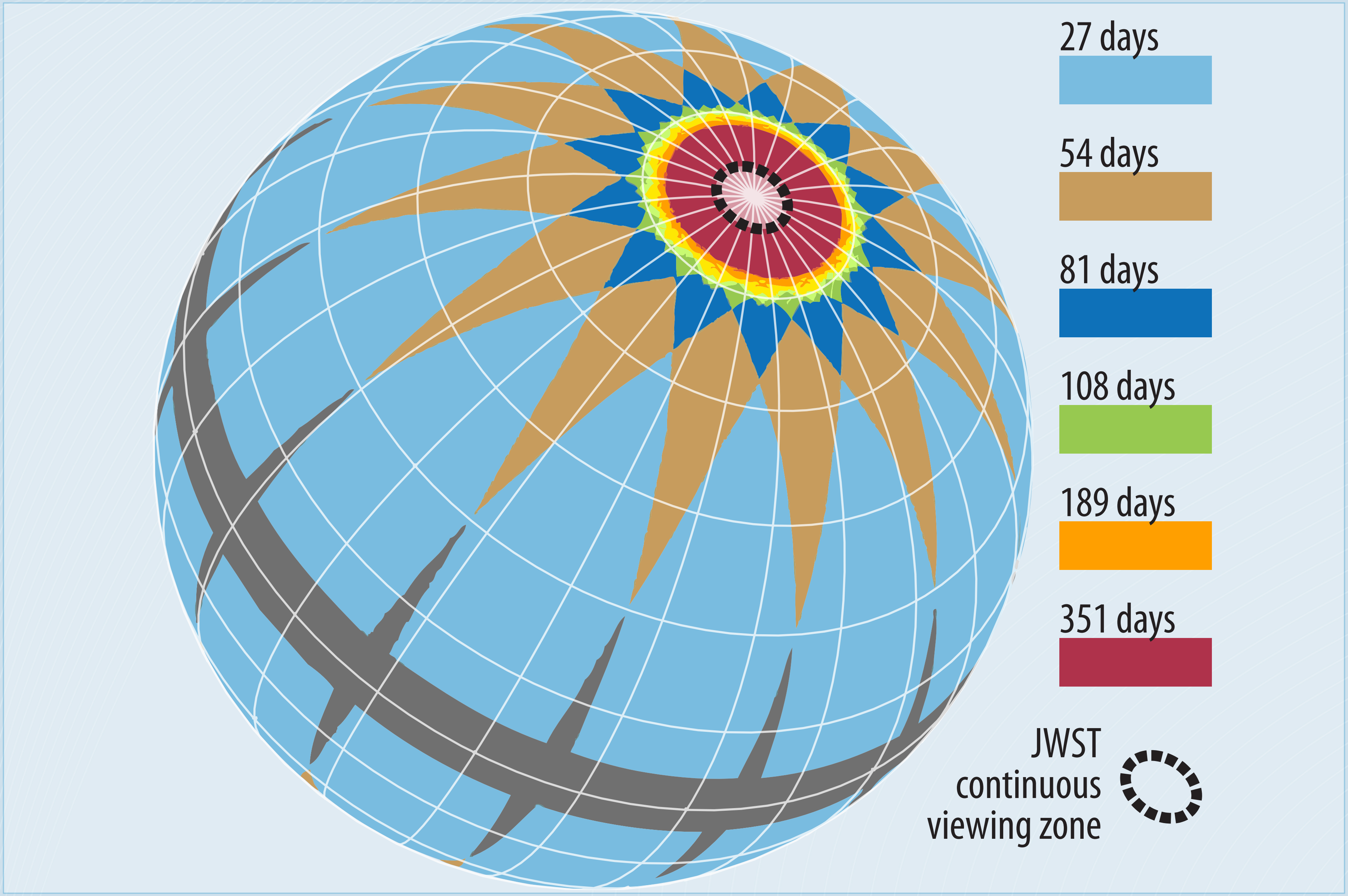
TESS Sky Mapping Plan





Ricker et al., JATIS, (2014)

TESS 2-year Sky Coverage Map



TESS's Novel High Orbit

Uninterrupted viewing for >95% of time

Orbital Periods:
TESS = 13.7 days
Moon = 27.4 days
➡ 2:1 Resonance
➡ 90° Phasing

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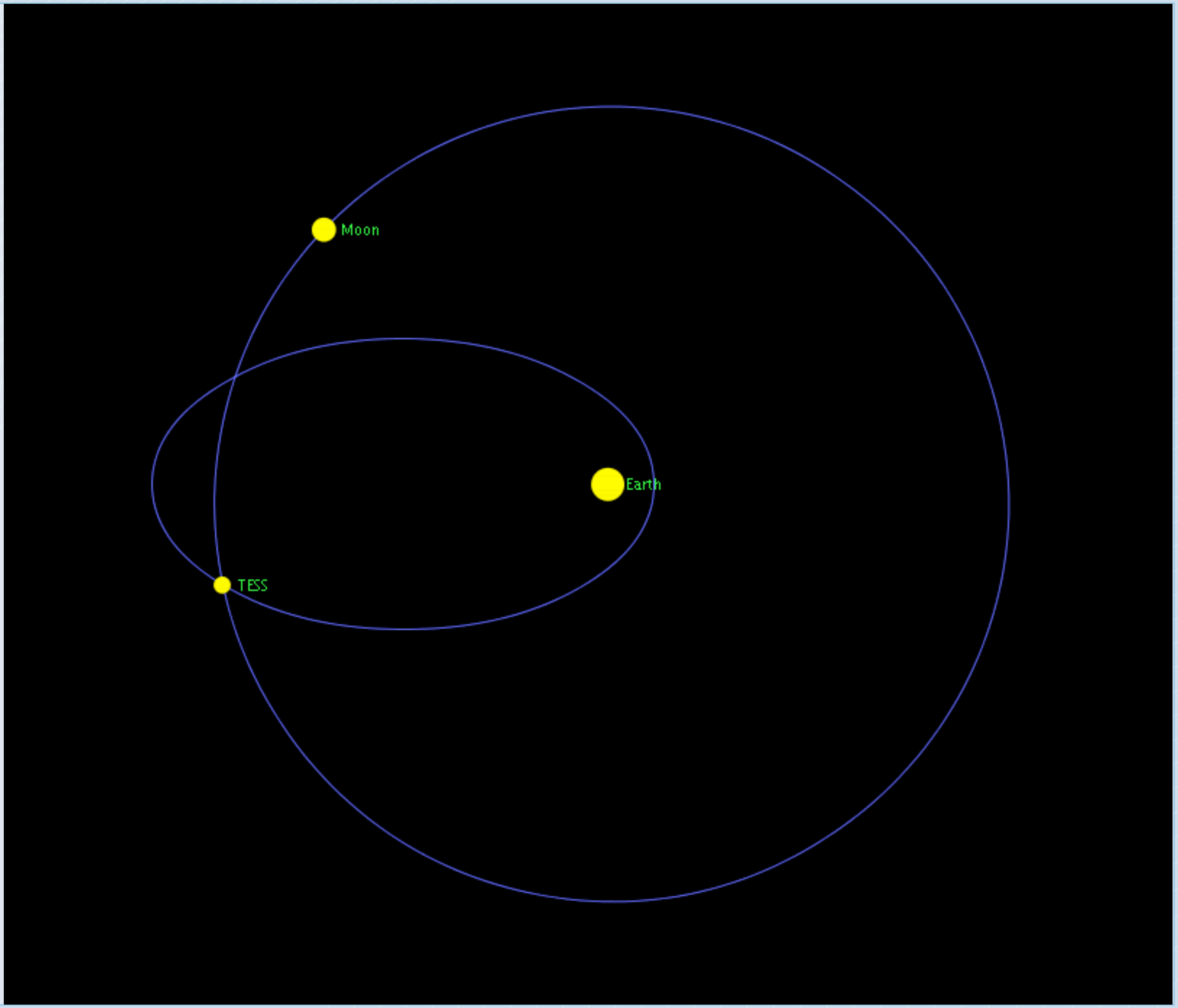

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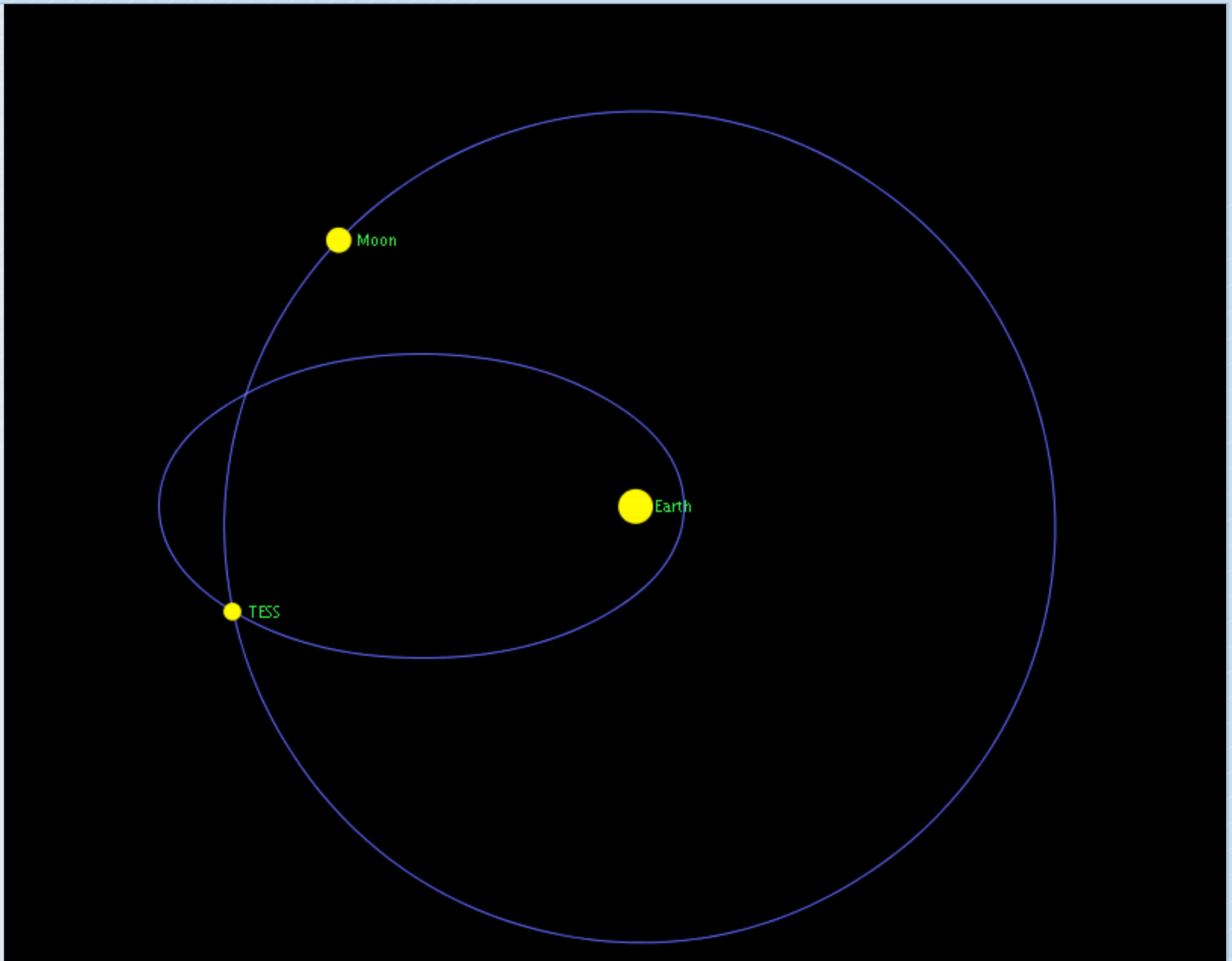

TESS Orbit is ***Stable*** for Decades *(no station keeping req'd)*

“Special” Orbit Enables and Simplifies TESS

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Provides seven major advantages:

"Special" Orbit Enables and Simplifies TESS

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- Extended & Unbroken Observations: *>300 hrs per orbit*
- Thermal Stability: *<40 mK/hr (passive control only)*
- Earth/Moon Stray Light Reduction: *10^6 times less than LEO*
- Low Radiation Levels: *Outside of Earth's Radiation Belts*
- Frequent Launch Windows: *Several days per lunar month*
- Excellent Pointing Stability: *No Drag, No Gravity Gradient*
- **High Data Rates:** *100 Mbit/s (200 GB in 4.5hr at Perigee)*

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➡ *$1/R^2$ advantage: ~ 23 dB gain over an L2 orbit*

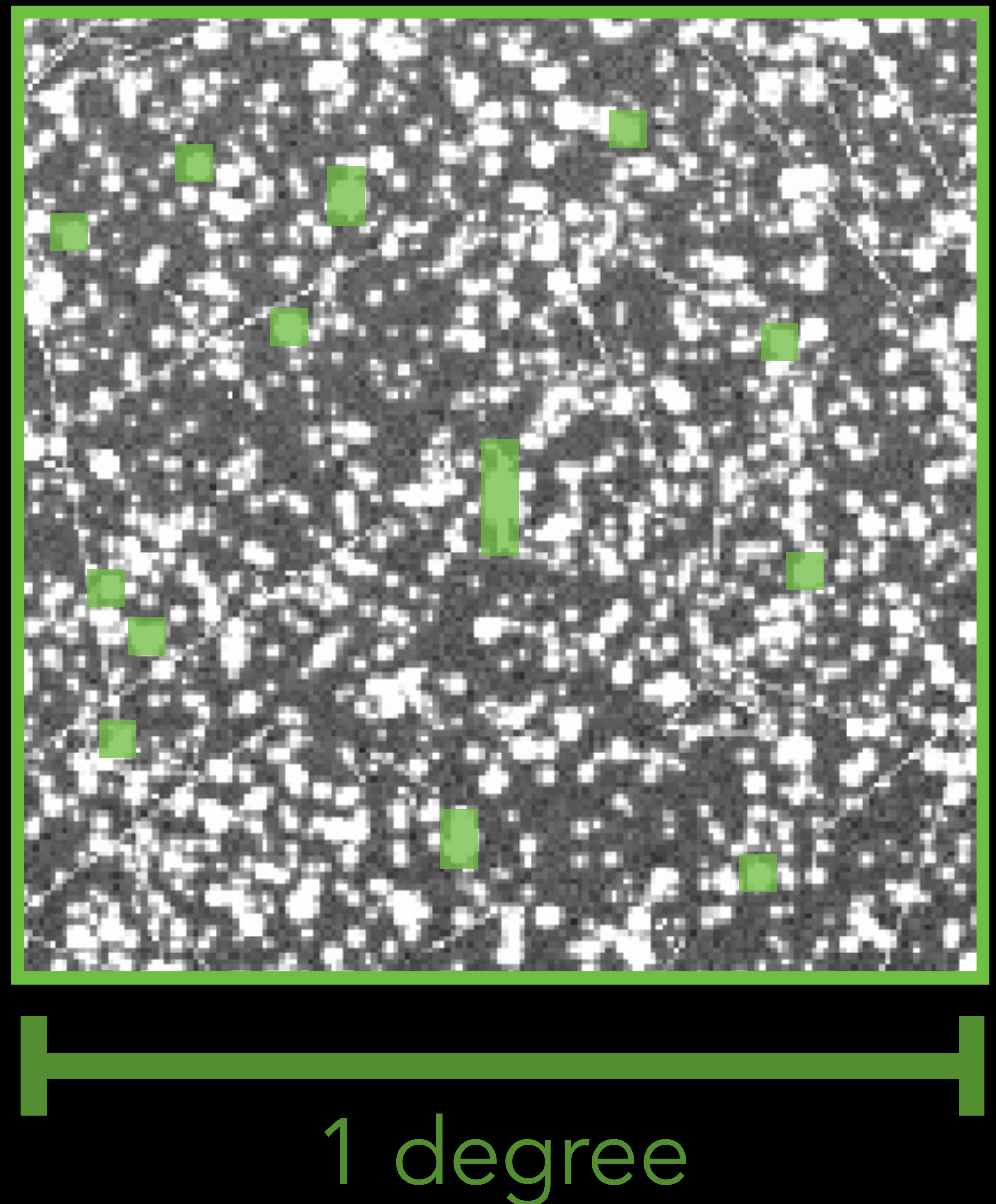
Gangestad et al. 2013 (astro-ph 1306.5333)

Q: What Will TESS Star Field Images Look Like?

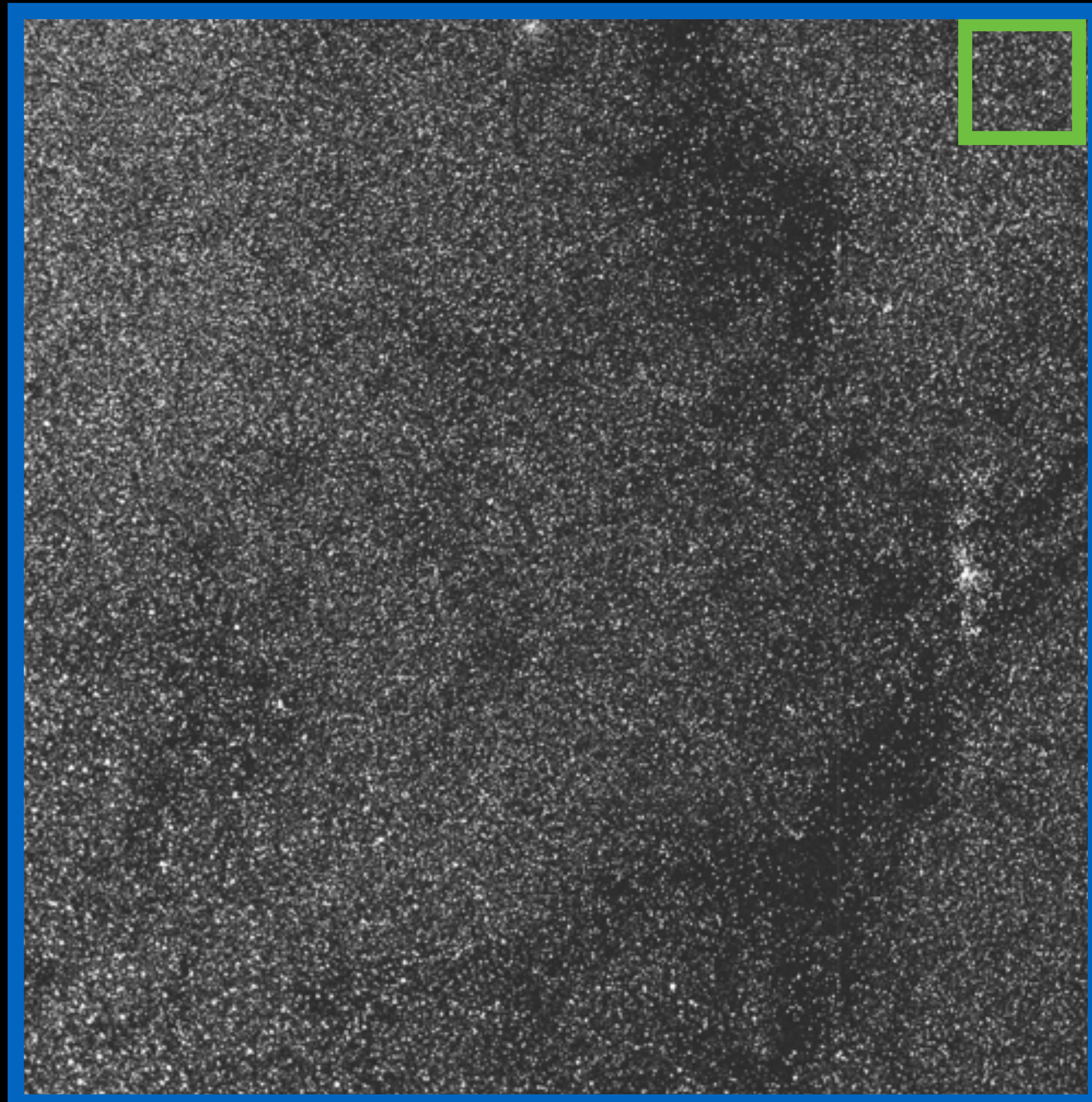
A: Use Model Simulations from Catalogs of Known Stars

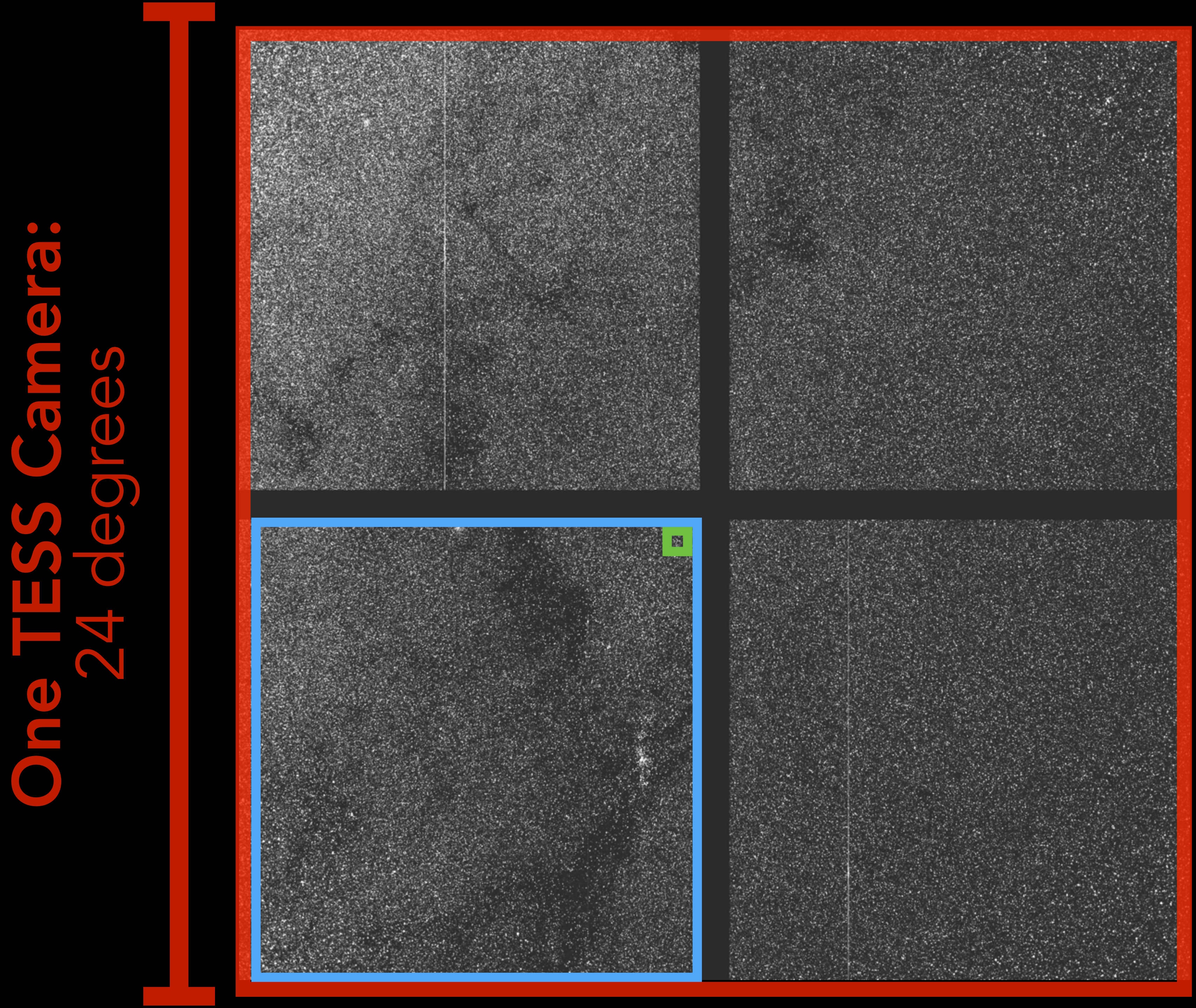
2-minute cadence
for 200,000 stars

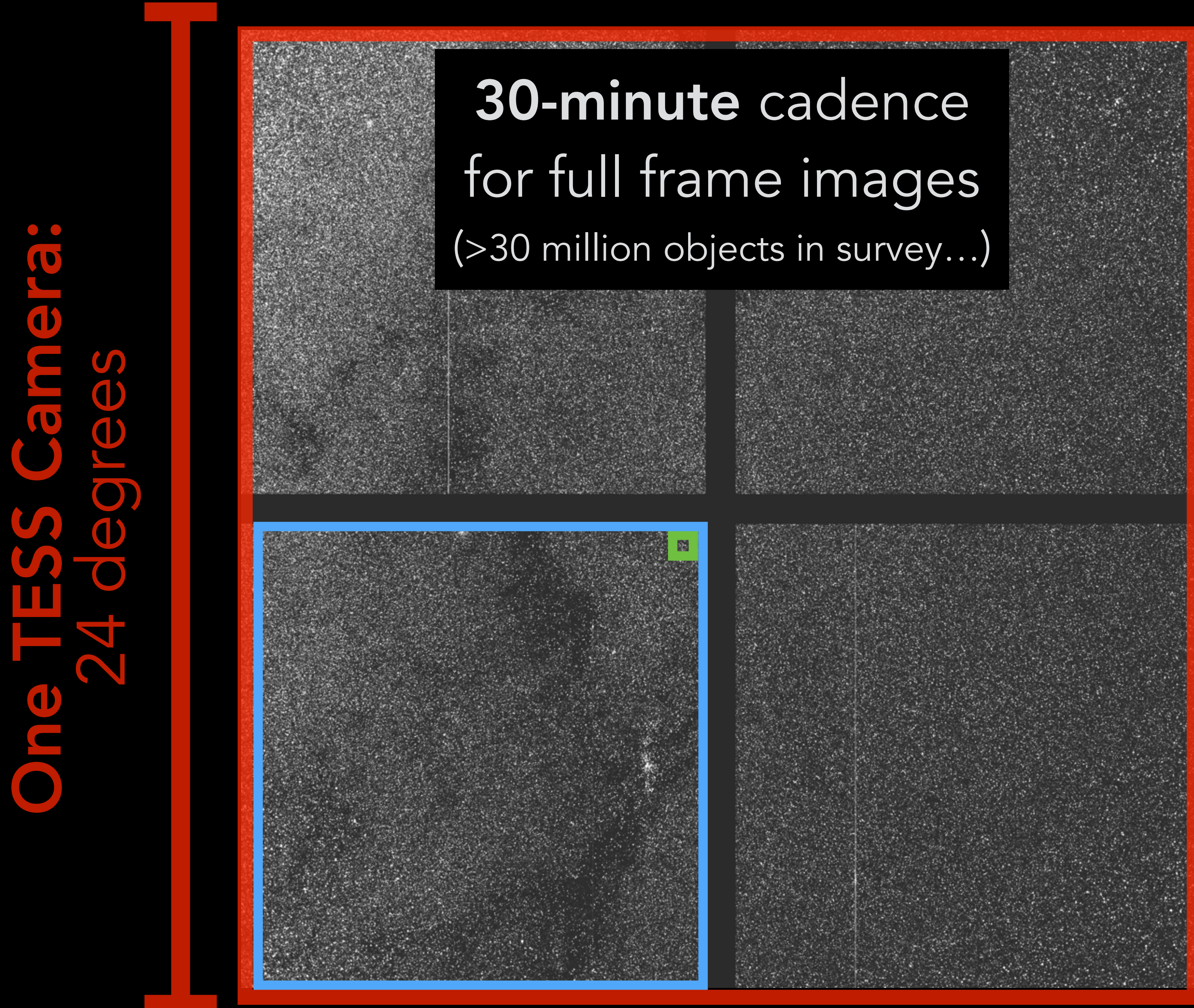
prioritizing detectability of small planets



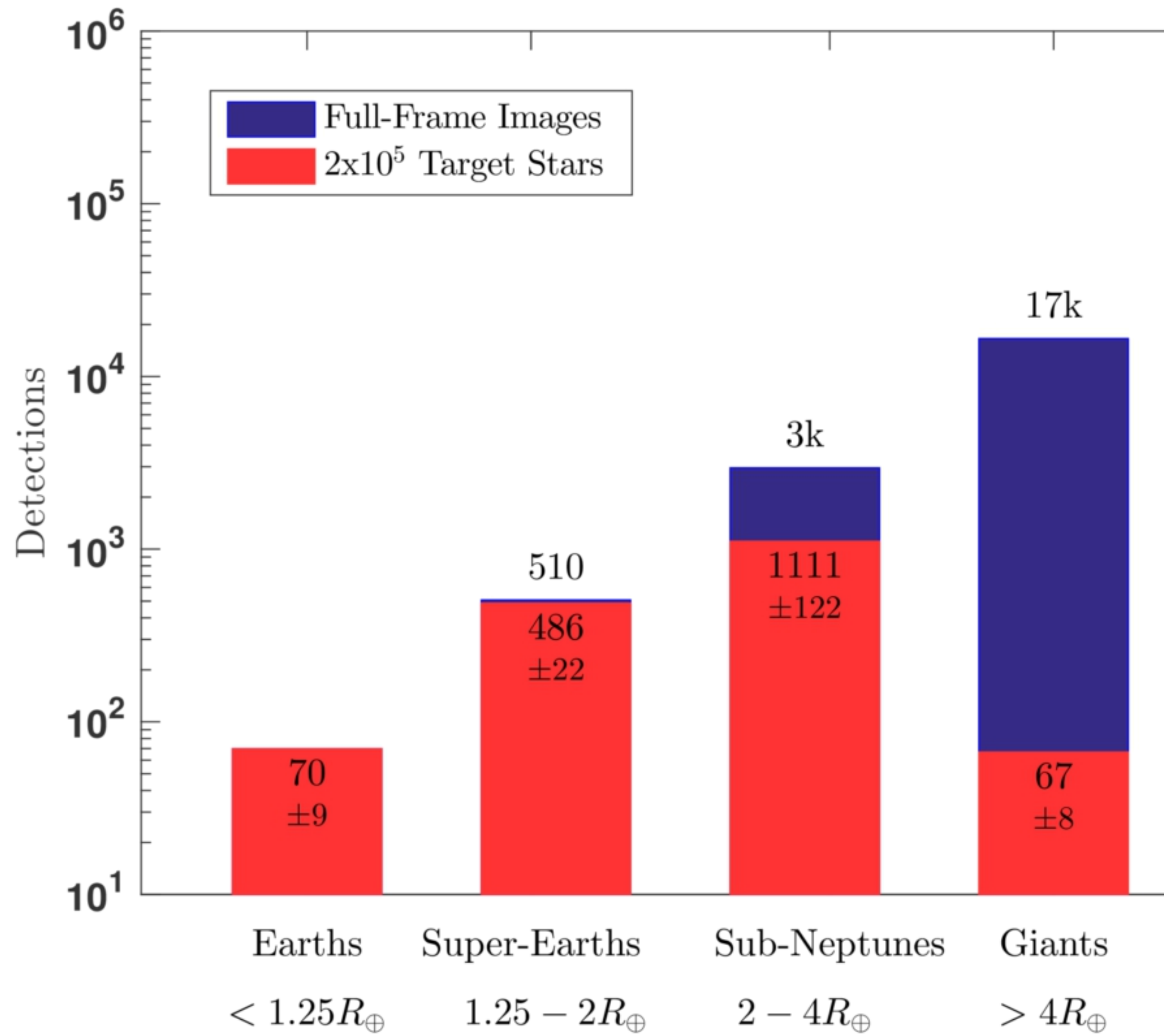
One TESS CCD:
12 degrees




One TESS Camera:
24 degrees


One TESS Camera:
24 degrees
30-minute cadence
for full frame images
(>30 million objects in survey…)

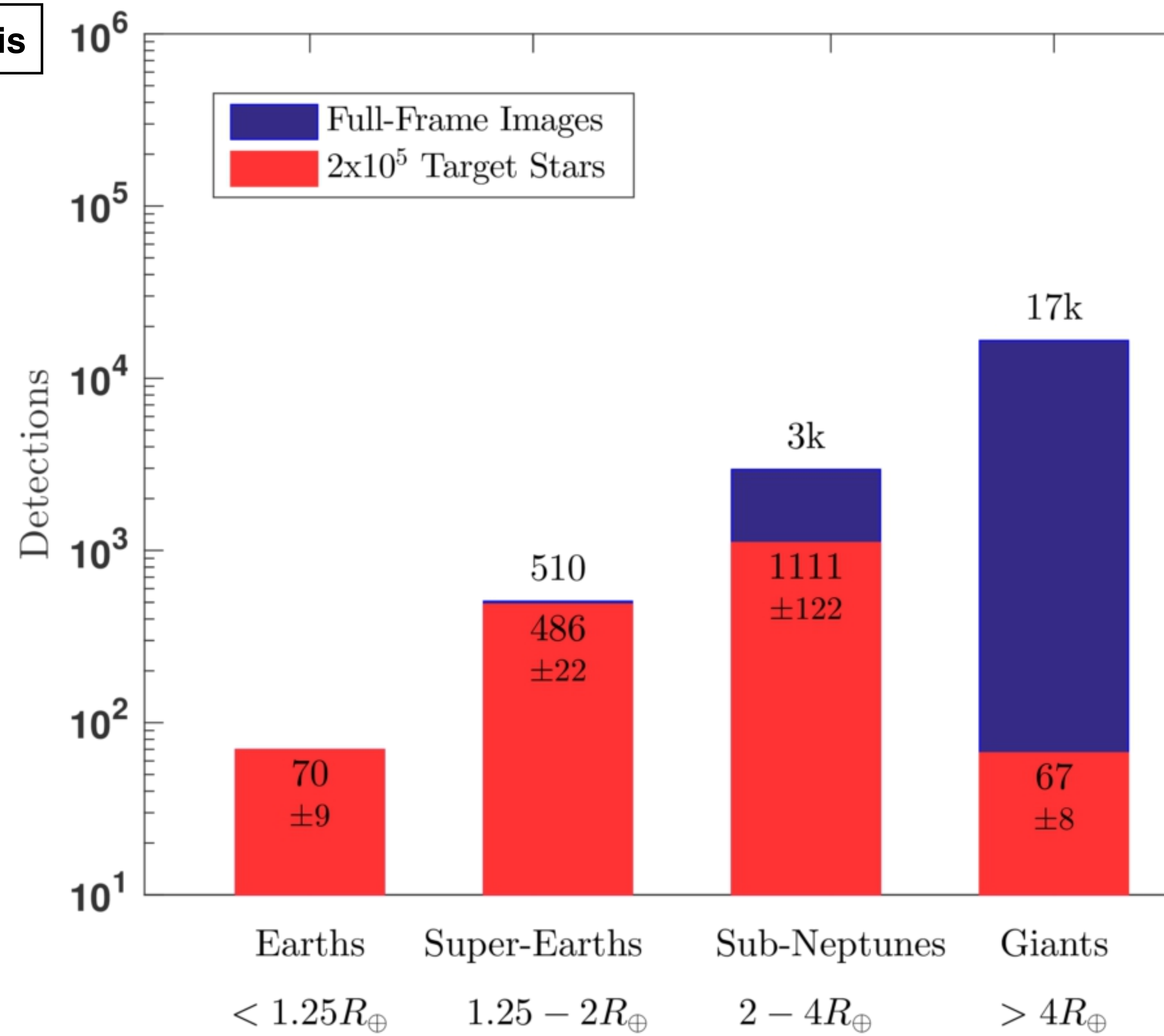
The Predicted TESS Yield



Sullivan et al. (arXiv:1506.08845)

The Predicted TESS Yield

NB: Log Scale on Y Axis



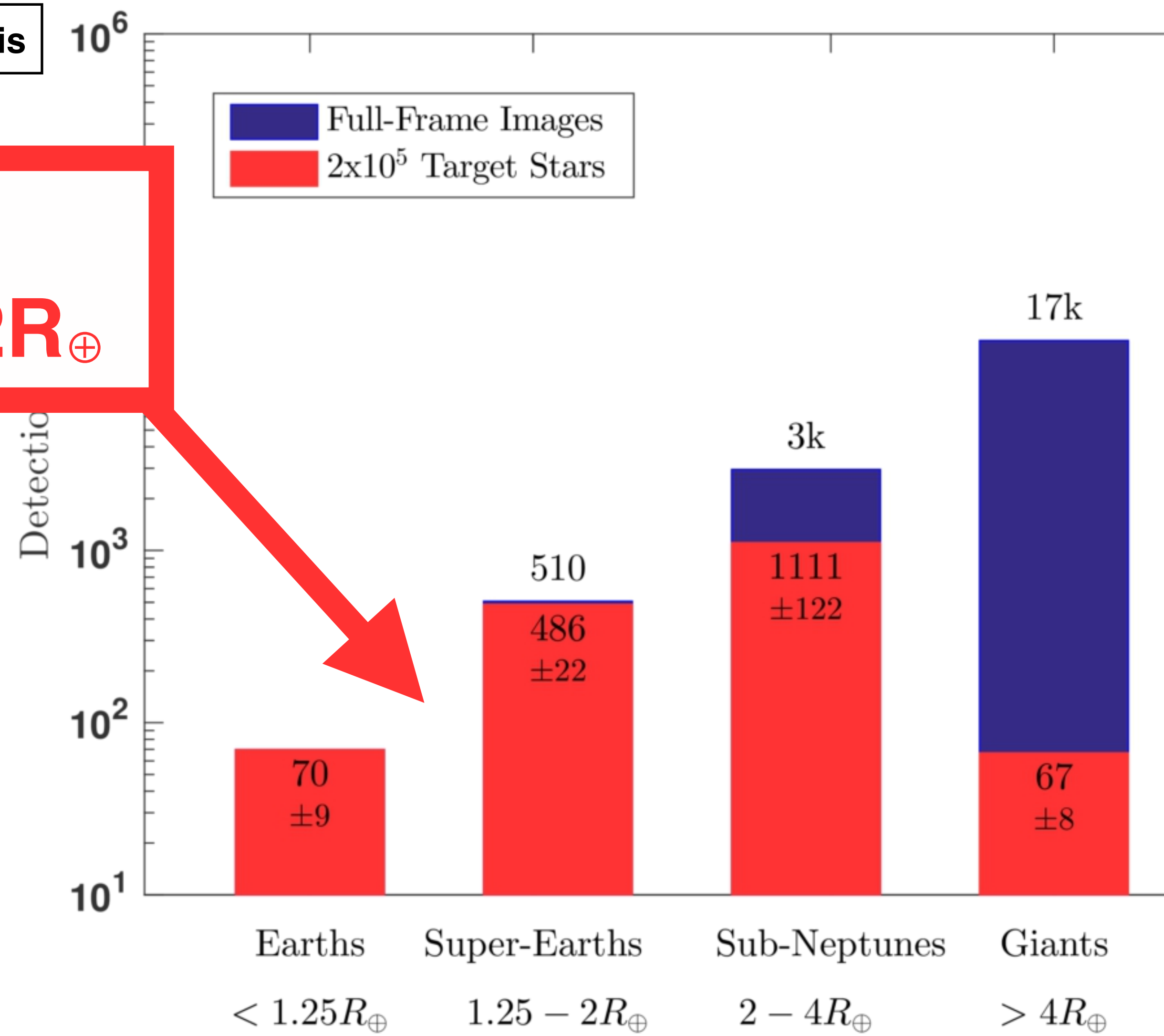
Sullivan et al. (arXiv:1506.08845)

The Predicted TESS Yield

NB: Log Scale on Y Axis

500 planets smaller than $2R_\oplus$

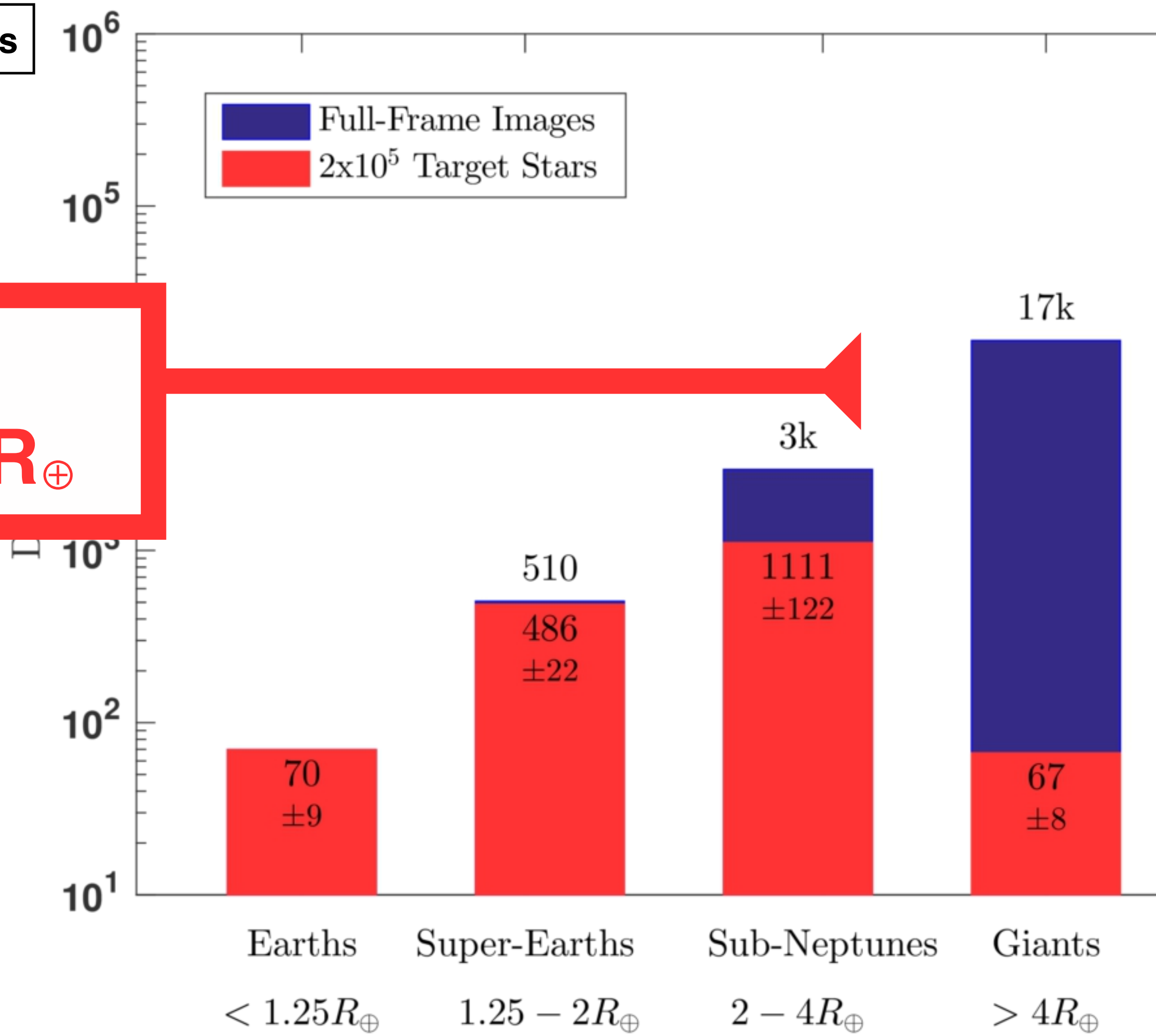
mass measurements could resolve the rocky planet transition



Sullivan et al. (arXiv:1506.08845)

The Predicted TESS Yield

NB: Log Scale on Y Axis



1500 planets smaller than $4R_\oplus$

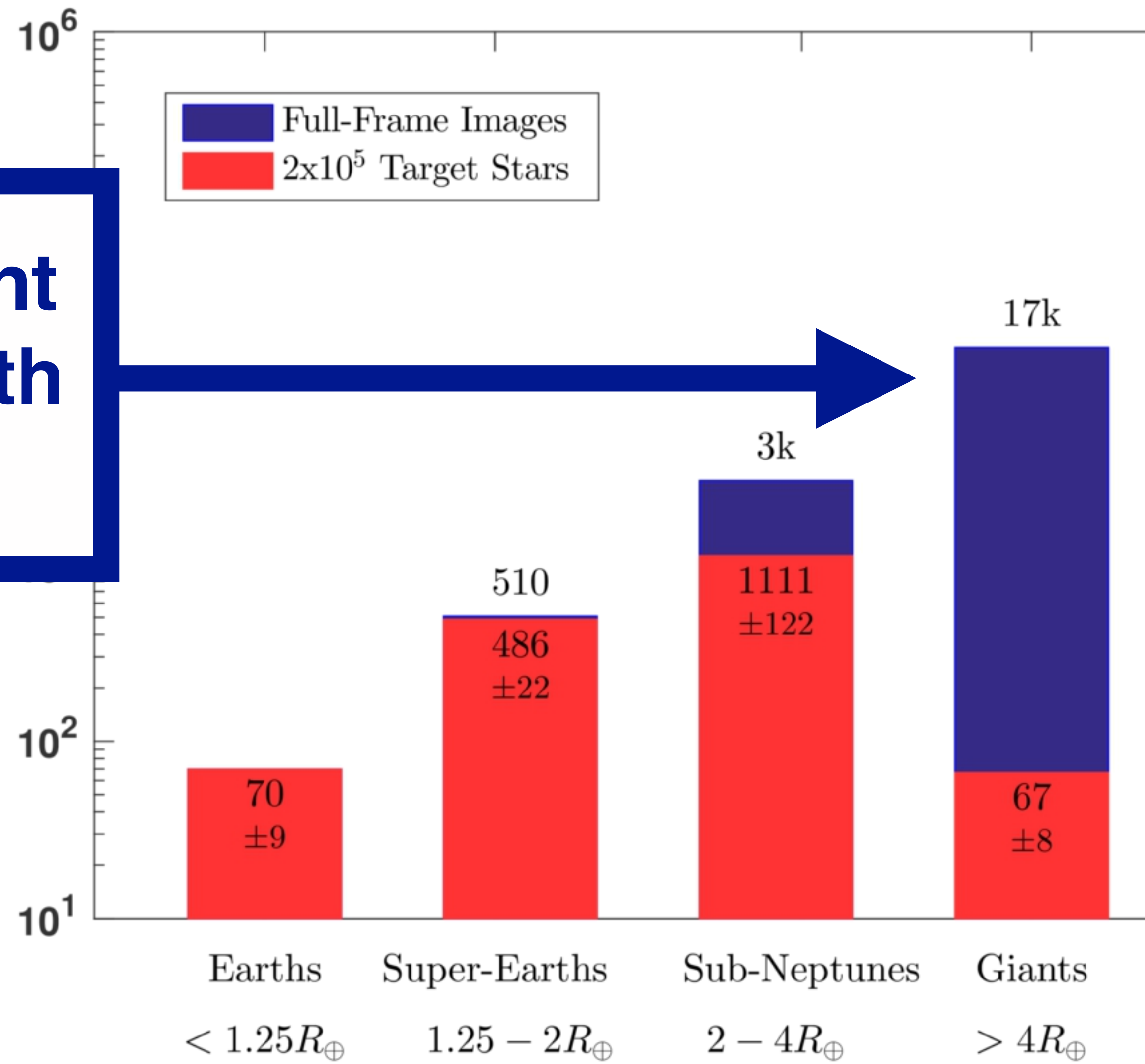
atmospheric studies will be possible for many of these

Sullivan et al. (arXiv:1506.08845)

The Predicted TESS Yield

NB: Log Scale on Y Axis

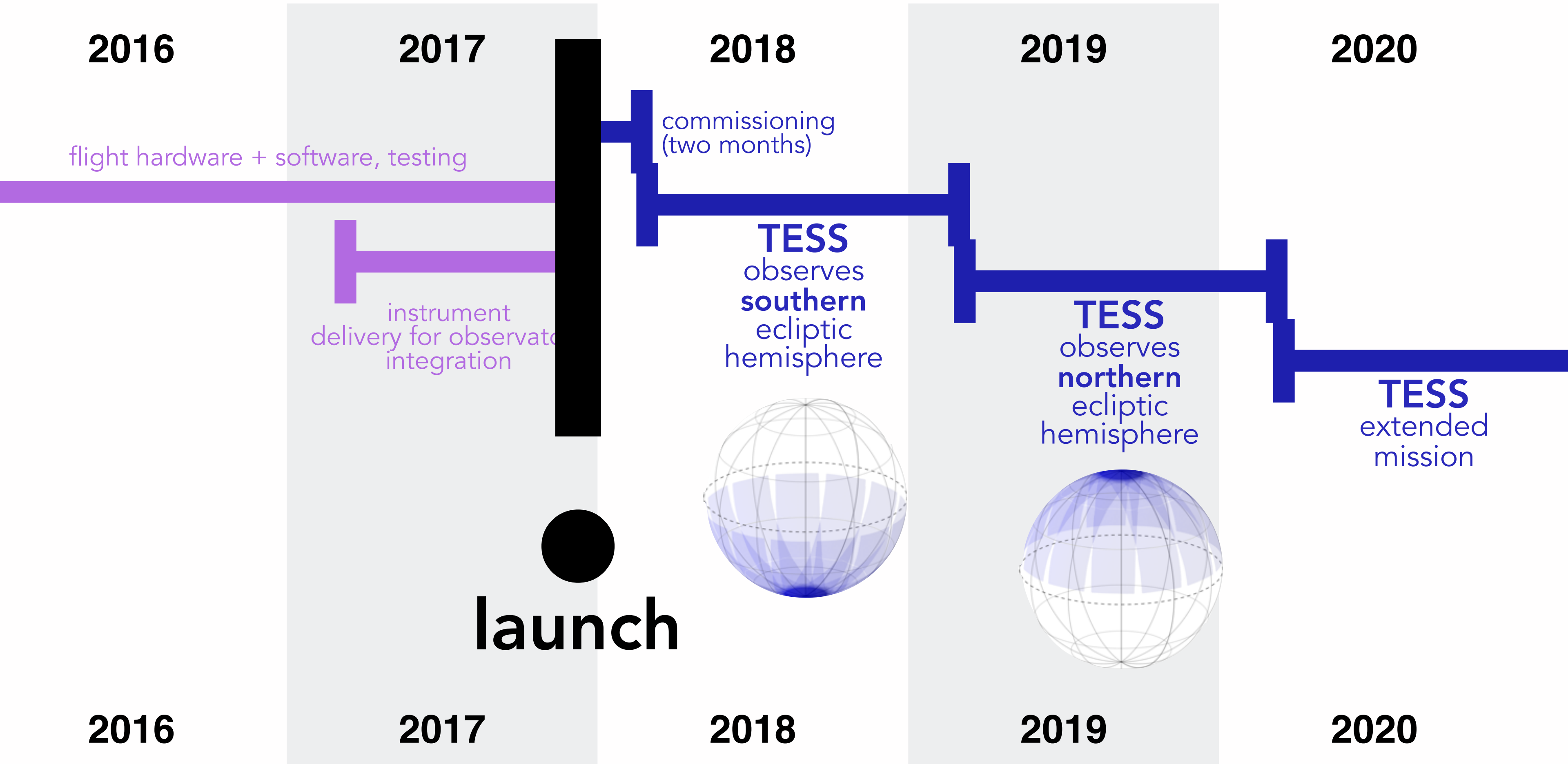
rare, distant, giant planets found with FFI's

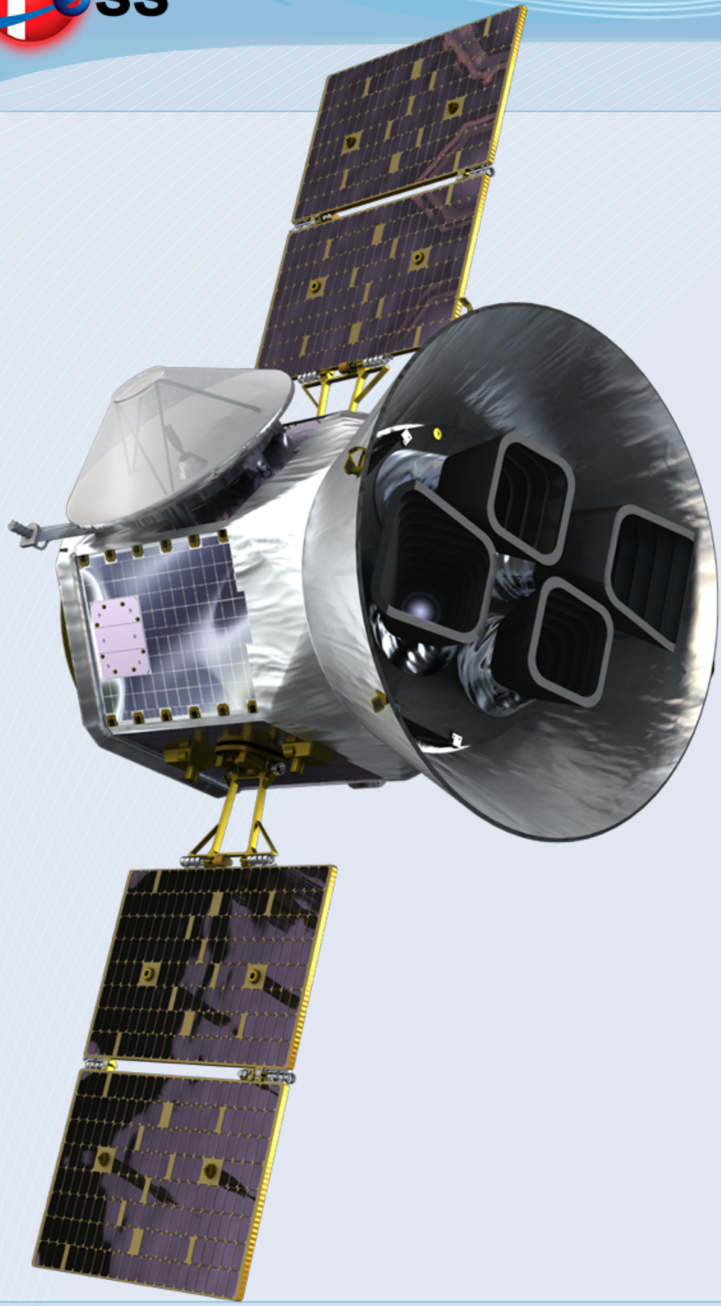


evolutionary studies of hot saturns and jupiters

Sullivan et al. (arXiv:1506.08845)

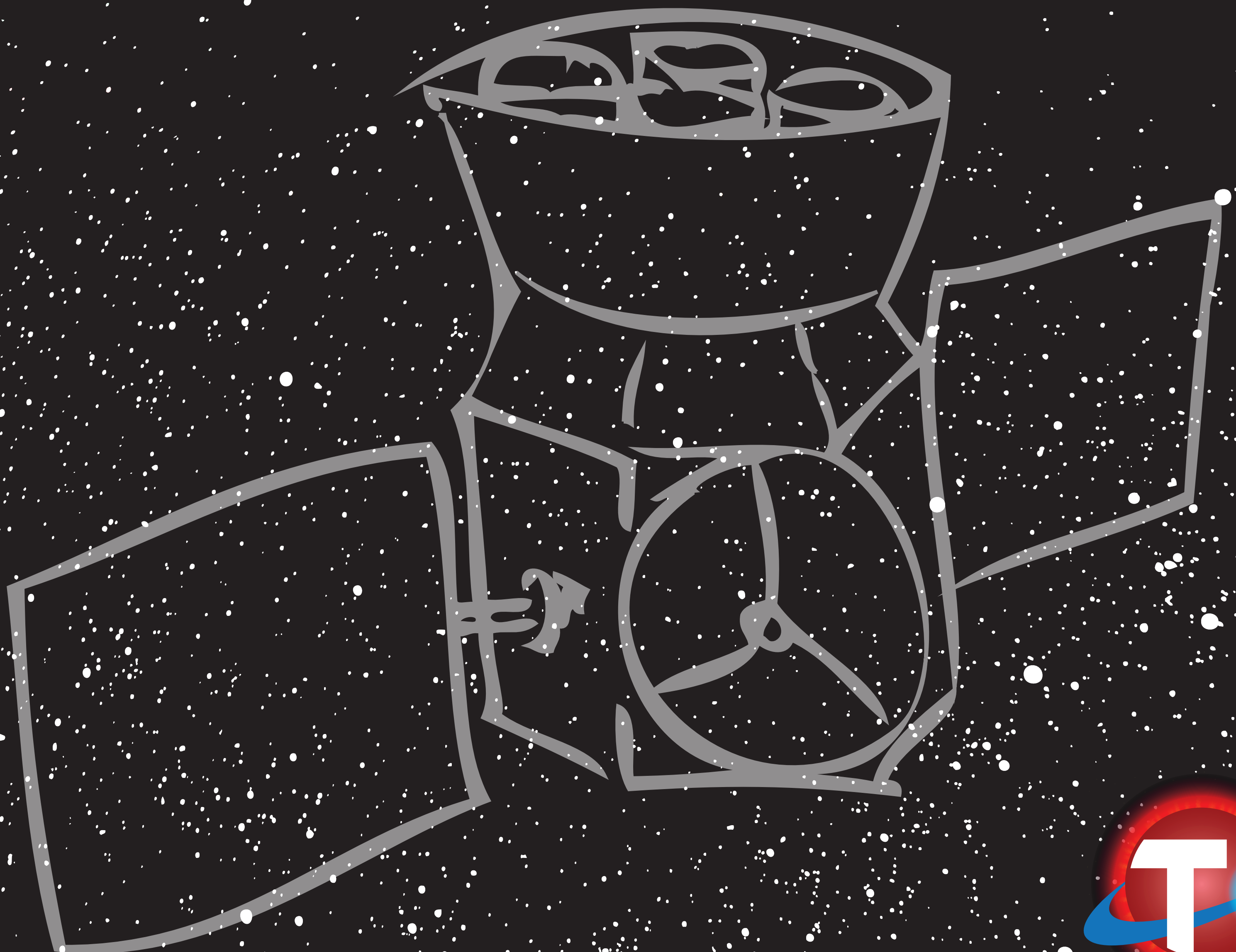
TESS timeline:





Takeaways

- TESS is needed to find nearby bright small transiting planets.
- TESS is being built and is on schedule to launch in late 2017.
- TESS could in principle operate for more than two decades
- The TESS planets will endure as the best small planet targets for radial velocity mass measurements and atmospheric characterization.



TESS